Elsevier Editorial System(tm) for Journal of Applied Geophysics
Manuscript Draft

Manuscript Number: APPGEO2963R1

Title: A study of the effect of seasonal climatic factors on the electrical resistivity response of three experimental graves

Article Type: Regular

Keywords: Near-surface geophysics; electrical resistivity; seasonal variation; forensic search; clandestine grave.

Corresponding Author: Dr. Jamie K Pringle, Ph.D, MA, BSc

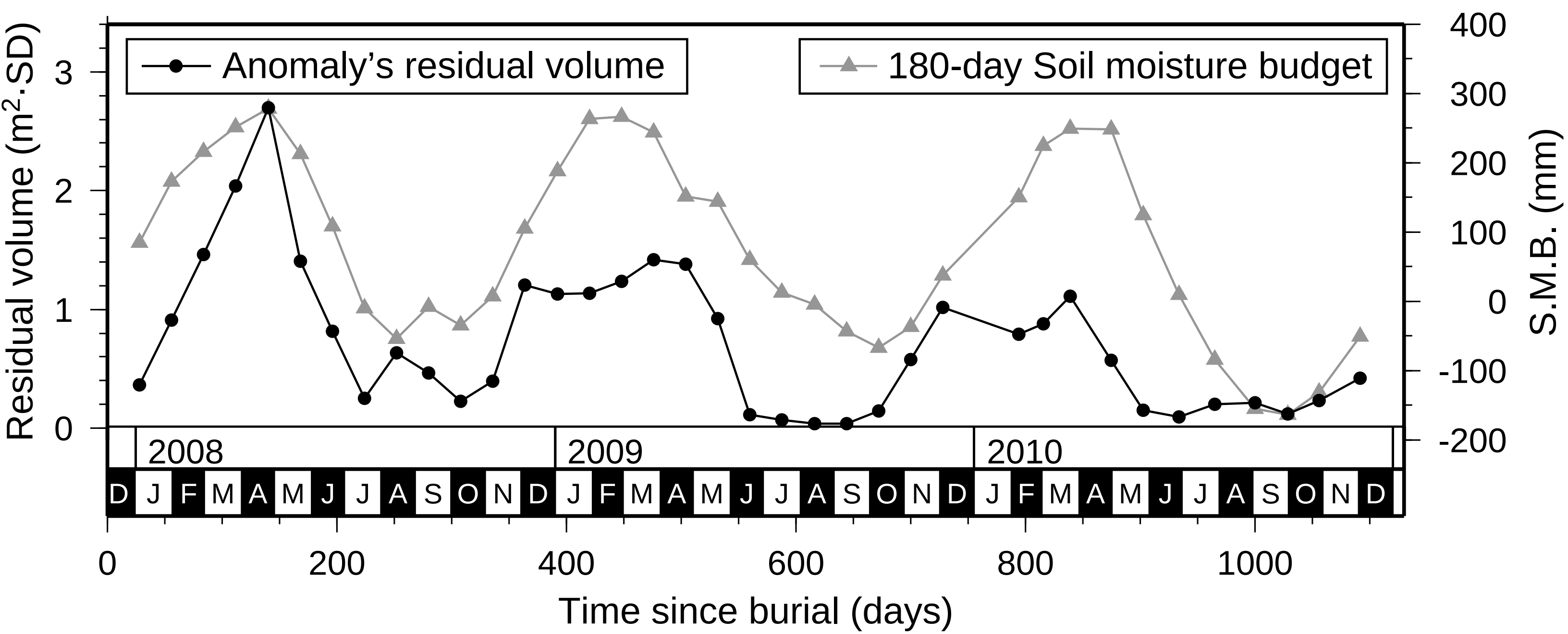
Corresponding Author's Institution: Keele University

First Author: John R Jervis, Ph.D, M.Sc, B.Sc

Order of Authors: John R Jervis, Ph.D, M.Sc, B.Sc; Jamie K Pringle, Ph.D, MA, BSc

Abstract: Electrical resistivity surveys have proven useful for locating clandestine graves in a number of forensic searches. However, some aspects of grave detection with resistivity surveys remain imperfectly understood. One such aspect is the effect of seasonal changes in climate on the resistivity response of graves. In this study, resistivity survey data collected over three years over three simulated graves were analysed in order to assess how the graves' resistivity anomalies varied seasonally and when they could most easily be detected. Thresholds were used to identify anomalies, and the 'residual volume' of grave-related anomalies was calculated as the area bounded by the relevant thresholds multiplied by the anomaly's average value above the threshold. The residual volume of a resistivity anomaly associated with a buried pig cadaver showed evidence of repeating annual patterns and was moderately correlated with the soil moisture budget. This anomaly was easiest to detect between January and April each year, after prolonged periods of high net gain in soil moisture. The resistivity response of a wrapped cadaver was more complex, although it also showed evidence of seasonal variation during the third year after burial. We suggest that the observed variation in the graves' resistivity anomalies was caused by seasonal change in survey data noise levels, which was in turn influenced by the soil moisture budget. It is possible that similar variations occur elsewhere for sites with seasonal climate variations and this could affect successful detection of other subsurface features. Further research to investigate how different climates and soil types affect seasonal variation in grave-related resistivity anomalies would be useful.

Graphical Abstract (for review)



***Research Highlights**

Highlights

- We analysed repeat resistivity survey datasets collected over two test graves
- The graves were easiest to detect after long periods of net soil moisture gain
- The best times for detection coincided with low noise levels in the survey data
- Resistivity data ~~may be~~were less noisy ~~if~~ when collected after long periods of wet weather

List of changes

This list refers to the version of the manuscript (and the highlights) with changes marked so that the alterations can be easily identified. Comments are listed in bold, and the amendments made are listed after each comment. Line numbers are given before the listed changes, but these no longer match with the line numbers given by reviewers because of the changes made to the manuscript.

Reviewer #1 … the strength of the general applicability of the results as suggested by the title of the paper is less clear. This is in part due to the limited number of graves in the study and so lack of replication, but also because there is not an empty control grave dataset included to allow the contribution of the body mass and decomposition fluids to the response to be disentangled from the response resulting purely from the fill and structure of a grave sized intrusion. If there is such control data available this should be included.

We have extended the results to include analysis of the data for an empty grave, which was within the original survey area (but was not included in the version of the manuscript that we initially submitted). The new results have also lead to a slight re-interpretation of the results for the other two graves. In response to this point, we have made the following changes:

Line 21: changed “two simulated graves” to “three simulated graves”

108-111 Changed “We focussed on two of these test graves: one contained a pig cadaver, and the other contained a pig cadaver wrapped in a tarpaulin” to “We focussed on three of these test graves: one contained a pig cadaver, the second did not contain a cadaver, and the third contained a pig cadaver wrapped in a tarpaulin”

111 Added “the ‘empty grave’”

121-122 Added “No obvious anomaly was observed for the empty grave (Jervis et al., 2009b; Pringle et al., 2012c).”

149-151 Changed “The two graves that we focussed on in this study were created on the 7th of December, 2007.” to “The empty grave was created on the 6th of December, 2007, and the pig grave and the wrapped pig grave were created on the 7th of December, 2007.”

151-153 Changed “Both graves were 0.5 m deep and contained a pig cadaver that weighed approximately 80 kg.” to “All three graves were 0.5 m deep. The empty grave contained only backfilled soil, and the pig grave and the wrapped pig grave both contained a pig cadaver that weighed approximately 80 kg.”

189 Changed “two sub-areas” to “sub-areas”

190 Changed “the two graves” to “the three graves”

267 Added a new sub-section “*3.2 The empty grave*”

269-278 Added “The empty grave was associated with a high resistivity anomaly (Fig. 6). This anomaly was absent for most of 2008, and its residual volume was less than 0.1 $m^2{\cdot}SD$ even when it was present. In 2009, the anomaly was present more often and its residual volume was slightly higher. There was a peak in the anomaly's residual volume between April and October, and its maximum value was 0.19 $m^2 \cdot SD$. The anomaly's residual volume was higher still in 2010, with a maximum value of 0.82 $m^2 \cdot SD$. There was a peak in the anomaly's residual volume between April and the end of the year. The residual volume of the empty grave's anomaly was not well correlated ($R^2<0.3$) with any of the soil moisture budgets. Similarly, the anomaly's residual volume was not well correlated with the inverse values of the average or the standard deviation of the raw datasets."

The subsequent sub-sections in the results have been re-numbered from "3.2" and "3.3" to "3.3" and "3.4" (lines 280 & 301).

355-363 Added "Although disturbed soil is usually expected to cause low resistivity anomalies, the empty grave in this study was associated with a high resistivity anomaly. This anomaly was not particularly noticeable during the first two years of the study, but it was more obvious in the third year. The year on year increase in this anomaly's residual volume could have been caused by the gradual drying out of the grave soil in dry weather. This explanation is consistent with the fact that the annual peaks in the anomaly's residual volume occurred in the summer months when the 30-day soil moisture budget was typically negative. It seems likely that disturbing the soil to create the grave affected the soil's ability to retain moisture."

365-371 Added "There may have been some seasonal variation in the empty grave's residual volume, even though it was not well correlated with the soil moisture budget. The rise and fall in the anomaly's residual volume in 2010 could have been the beginning of an annual pattern. The 2010 peak in the anomaly's residual volume occurred when the 30-, 60- and 90-day soil moisture budgets were negative. The grave's resistivity could, therefore, have been a result of seasonal wetting and drying of the grave soil that was a result of changes in the short-term soil moisture budget."

393-395 Added "Another possibility is that the grave soil gradually dried out (as we suggest happened in the empty grave), and the corresponding rise in soil resistivity counteracted the low resistivity effect of the grave fluid."

412-414 Added "Alternatively, as with the empty grave, the increase in the high resistivity anomaly's volume towards the end of the study could have been caused by the grave soil's drying out."

607 Changed "two graves" to "three graves"

610 Added "the empty grave is in the centre,"

615 Added ", the empty grave,"

We have also added a new figure, which shows how the residual volume of the empty grave varied throughout the study period. This has become the new fig. 6 and the old figs. 6, 7 & 8 have become figs. 7, 8 & 9 respectively. Because of this we have made the following changes:

283 Changed "Fig. 6" to "Fig. 7"

295 Changed “Fig. 7” to “Fig. 8”

304 Changed “Fig. 8” to “Fig. 9”

376-377 Changed “Fig. 1 cf. Fig. 6” to “Fig. 1 cf. Fig. 7”

636-637 Added “Figure 6: The residual volume of the empty grave anomaly. Asterisks indicate values calculated from the two datasets shown in Fig. 1.”

639 Changed “Figure 6” to “Figure 7”

642 Changed “Figure 7” to “Figure 8”

648 Changed “Figure 8” to “Figure 9”

Title - I do not think the title truly reflects the rather specific subject matter and should be more along the lines A study of the effect of seasonal climatic factors on the electrical resistivity responses of two experimental graves.

1-3 Changed the title to “A study of the effect of seasonal climatic factors on the electrical resistivity responses of three experimental graves”

Abstract: Removal of the semi colon and rewording that sentence.

17-20 Replaced “However, not all have been successful; seasonal changes in climate can affect resistivity survey results” with “However, some aspects of grave detection with resistivity surveys remain imperfectly understood. One such aspect is the effect of seasonal changes in climate on the resistivity response of graves.”

Need to specify 'the graves' not just any and all graves as the wording suggests.

21-23 Replaced “in order to assess how graves' resistivity anomalies vary seasonally and when surveys are optimal” with “in order to assess how the graves' resistivity anomalies varied seasonally and when they could most easily be detected”

32-33 Changed “variation in graves’ resistivity anomalies” to “variation in the graves’ resistivity anomalies”.

Suggest that the novel method of calculating anomaly 'volumes' be mentioned in the abstract as this is key to the methodological approach taken.

23-25 Added ‘‘Thresholds were used to identify anomalies, and the ‘ residual volume’ of grave-related anomalies was calculated as the area bounded by the relevant thresholds multiplied by the anomaly’s average value above the threshold.”

26-29 This addition allows the results to be better explained. As such, we have replaced “Geophysical anomalies, associated with an animal cadaver, were easiest to detect between January to April” with “The residual volume of a resistivity anomaly associated with a buried pig cadaver showed evidence of repeating annual patterns and was moderately correlated with the soil moisture budget. This anomaly was easiest to detect between January and April”

Suggest adding lines 409-411 (or similar) to the end of the abstract to clarify where future research should be directed.

36-38 Added “Further research to investigate how different climates and soil types affect seasonal variation in grave-related resistivity anomalies would be useful.”

The units on the diagram need sorting out as a m2 'volume' is not just slightly counter-intuitive it is confusing and incorrect as m2 quantifies an area and so cannot be used for any sort of a volume - see suggestions below.

Change the units in the graphical abstract to $m^2 \cdot SD$

Highlights
The last one needs attention. Is the resistivity data less noisy or is it not after long periods wet weather? If the 'may be' is because sometimes it is or sometimes it isn't then this observation seems not particularly useful.

Replaced “Resistivity data may be less noisy if collected after long periods of wet weather” with “Resistivity data were less noisy when collected after long periods of wet weather”

48-49 - some 'areas' of grave detection - suggest 'aspects' of grave and can you clarify the 'some' with examples or just add that these incompletely understood aspects include seasonal variation.

59 Replaced “areas” with “aspects”

60-62 Added “For example, the effects of soil type and seasonal changes in soil resistivity on the resistivity response of graves are not fully understood.”

63 - 'can' replace with 'will' or 'normally will' or similar otherwise the whole basis of the research is in question.

76 Replaced “can” with “will”

71 replace 'ancient' with 'archaeological' - ancient has a more specific period definition in that relates to largely to prehistoric periods and in particular to Mediterranean cultures
Ditto line 76 - 'archaeological' graves

84 Replaced “ancient” with “archaeological”

89-90 Replaced “ancient” with “archaeological”

70-71 need to also note the strong influence of soils/geology evident in Clark's results

91-102 Changed “Explanations offered for seasonal variation in the appearance of resistivity anomalies include: changes in near-surface soil resistivity affecting the depth of investigation of the surveys; and differences between the moisture retention characteristics of the feature that caused the anomaly and those of the surrounding soil (Clark, 1996; Scollar et al., 1990).” to “Seasonal variation in the appearance of resistivity anomalies can be caused by differences between the moisture retention characteristics of the feature that caused the anomaly and those of the surrounding soil (Clark, 1996; Scollar et al., 1990). As such, different soil types and local geological conditions can influence the seasonal variation in a resistivity anomaly. For example, Clark (1996) found the seasonal variation in ditches at locations with chalk bedrock to be unusual compared to that observed at locations with different geologies. Another possible cause of seasonal variation in resistivity anomalies is change in the effective depth of resistivity measurements, which is caused by seasonal change in the resistivity of near-surface soils."

87 - can you state the nature of the tarpaulin and whether is a impervious membrane or not here.

110 Changed "a tarpaulin" to "a porous tarpaulin made of woven polyethelene strands"

92-96 This has been observed on burials wrapped totally sealed in layers of heavy grade polythene that cannot have leaked and so may be related to the material affecting transpiration or acting as a condensing surface.

120-122 Added "Alternatively, these anomalies may have been caused by a pool of percolating soil-water that had become trapped on the uppermost side of the tarpaulin."

134 Can you please give details of how you calculated the resistivity for your array configuration?

167-170 Changed "During data processing, each digital dataset was despiked" to "During data processing, the values in each dataset were converted from resistance to resistivity by multiplication by an appropriate geomtric factor (see e.g. Reynolds, 2011). For the electrode arrangement described above, the geometric factor was $34\pi/49$. The resistivity datasets were then de-spiked"

139 - how were the anomalous data points despiked? And why was the data set interpolated prior to de-trending?

170-172 Changed "resistivity datasets were then de-spiked (to remove anomalous datapoints), interpolated to a cell size of 0.125 m by 0.125 m and then de-trended" to "resistivity datasets were then de-spiked by visually identifying and removing isolated outliers, and interpolated to a cell size of 0.125 m by 0.125 m to aid visual interpretation. Each dataset was subsequently de-trended"

151 - the SD values (1?) were taken as 'a measure' of the noise levels rather than 'represent' the noise levels as this suggests (1?)SD is some sort of a valid measure of noise from signal when SD will be strongly affected by the presence or real anomalies.

184-185 Replaced "taken to represent" with "used as a measure of"

159 - remove 'often' - resistivity anomalies always extend beyond the physical limits of the feature that causes the anomaly as current flow in affected

192 Removed "often"

161-163 add SD to the +-2

194-196 Changed "+2" to "+2 SD", "-2" to "-2 SD", and "±2" to "±2 SD".

167
This is the main issue, the use of the 'volume' - in this line it certainly needs to be in inverted commas.
I would suggest that you simply refer to this as 'apparent volume' or the something like 'residual SD volume' (rSD) or 'average residual SD (arSD) by defining rSD as the average of values greater than +/-2SD. As it is the product of the area and value then the units would then be m2.rSD which would all make sense as a 'volume' both in the text, diagrams and captions.

We have opted to rename our "volume" value from the original manuscript as the "residual volume". We have changed the explanation of this value and changed "volume" to "residual volume" throughout the text.

200 Put inverted commas around "volume"

202-204 Changed "the difference between the anomaly's average value and the threshold" to "the average residual value of the anomaly, which we define as the difference between the anomaly's average value and the threshold"

204-205 Changed "a normalised value that had no units" to "a normalised value (measured in standard deviations)"

205-208 Replaced "Consequently chosen volume values had the slightly counter-intuitive units of m^2, but this 'volume' was the most satisfactory term for this quantity" with "As such, we shall refer to this quantity, which had units of $m^2 \cdot SD$, as an anomaly's 'residual volume."

208-209 Changed "volume estimate" to "residual volume"

219, 235, 242, 303, 304, 306, 307, 320 & 614 Changed "volumes" to "residual volumes"

282, 283, 285, 286, 289, 291, 294, 295, 305, 310, 311, 312, 313, 317, 373, 375-376, 384, 386, 387, 391, 397, 398, 399, 402, 404, 405, 410, 411, 414, 415, 417, 418, 422, 424, 426, 429, 430, 432, 434, 473, 618, 639, 642, 644 & 648 Changed "volume" to "residual volume"

Fig 7 (left axis), Fig 8b (left axis) & Fig 9 (left and right axes): Changed "Volume" to "Residual volume"

206 This really does need attention as values like 0.5 m2 in the text without qualification does not work in my opinion. 0.5 m2.rSD or similar provides clarity and solves the problem.

284, 285, 287, 310, 313, 314 & 318 Replaced "m^2" with "$m^2 \cdot SD$"

Fig 7 (left axis), Fig 8b (left axis) & Fig 9 (left and right axes): Replaced "(m^2)" with "($m^2 \cdot SD$)"

260 - Just to note that the high resistivity anomaly would be relatively large as resistive features produce a relatively stronger anomaly than low resistance anomalies of comparably resistivity contrast due to the geometry of the current flow.

The reviewer doesn't seem to be asking for any changes to be made here – it's more an interesting observation than a suggestion for improvement. As such, we have not made any changes in response to this point.

301 - it is a low topsoil resistance that restricts the current flow at depth as most current flows preferentially through the upper conductive layer - but this wetness does reduce the heterogeneities encountered in dryer topsoil and so reduces topsoil noise resulting, rather counter-intuitively, in sometimes making deeper anomalies more easily detectable.
as such I would suggest that your first possibility is likely to be correct and the alternative is not supported.

351-353 Removed "Alternatively, higher soil resistivity during dry periods may have restricted the depth of investigation of the resistivity surveys to more heterogeneous soil nearer the ground surface."

Acknowledgements
Suggest the organisation and position of one Jamie Hansen should be specified?

492 Added "(a PhD student at Keele University)" to describe Jamie Hansen's position and affiliation

The last two sentences seem contradictory - if the study was partially based on funded research then they had involvement, for which appropriate acknowledgement is needed, but the last sentence seems superfluous or suggest needs noting as 'any direct involvement' if it is to remain.

497 Removed "Neither of these funding sources had any involvement in this research."

Captions
529 - Example 'processed' resistivity data set and after (March 2010) add an explanation like 'demonstrating seasonal variation.'

606 Changed "Example resistivity survey datasets" to "Example processed resistivity survey datasets"

608 Added ", and demonstrating the seasonal variation in the data"

543 fig 3 a more informative caption is required - what does this show?

622-625 Added "The moisture budgets are typically positive in the early part of each year (especially January to June) and negative in the latter part of the year (July to November). This pattern becomes more pronounced as the period over which the moisture budget is calculated increases."

<u>Other changes</u>

12 Added a contact e-mail address for John Jervis

31 Changed double comma to a single comma

31 Changed "although also" to "although it also"

34 Changed “It is suggested” to “It is possible” to avoid using suggested twice in consecutive sentences

35 Changed “with” to “for”

70 Removed extra line break before section 1.1

89 Changed “proportion” to “proportional”

95 Changed “caused” to “causes”

130 Added “were moderately”

132 Changed double space between “years’” and “datasets” to a single space

141 Changed “here” to “in this section” to avoid repeating ‘here’ in consecutive sentences

154 Changed “is” to “was”

155 Changed “(Jervis et al., 2009)” to “(Jervis et al., 2009b)”

161 Changed “1 m apart at the same position at a distance of 17 m from the survey area” to “1 m apart at a position that was 17 m from the survey area”

183 Changed “raw data after de-spiking was” to “the raw datasets after de-spiking were”

184 Removed “(see Fig. 1)”

213-214 Removed extra line breaks before section 2.5

220 Removed “in distance”

223 Changed “was” to “were”

236-237 Removed extra line breaks before section 2.6

248 Removed extra line break before section 3

255 Replaced “.” with “·”

287 Changed “(~0.04 m^2)” to “, was ~0.04 m^2”

321 Changed “average” to “averages” and “standard deviation” to “standard deviations”

324 Removed extra line break before section 4

327 Removed “survey”

328 Removed “of the same target”

332 Changed “was” to “were”

373 Removed “also”

397 Changed “suggest” to “suggests”

443 Changed “were” to “was”

445-446 Changed “Binley et al., 2002” to “Clark, 1996”

455 Removed extra line break before section 5

462 “Changed “to” to “and”

488 Removed extra line break

496 Changed “EPSRC” to “the EPSRC”

497-498 Added “The comments of two anonymous reviewers helped to improve this paper.”

Graphical abstract – added the 180-day soil moisture budget to show the similarity between this and the pig grave anomaly’s residual volume

A study of the effect of seasonal climatic factors on the ~~ability of~~ electrical resistivity ~~surveys to detect~~response of three experimental ~~clandestine~~ graves

John R. Jervis[a]~~[1]~~, Jamie K. Pringle[a,]*

[a]School of Physical Sciences and Geography, Keele University, Keele, Staffordshire, ST5 5BG, UK.

*Corresponding author. Tel.: +44 1782 733163.

E-mail addresses: j.jervis@keele.ac.uk (J. Jervis), j.k.pringle@keele.ac.uk (J. Pringle).

Abstract

Electrical resistivity surveys have proven useful for locating clandestine graves in a number of forensic searches. However, ~~not all have been successful; seasonal changes in climate can affect resistivity survey results.~~some aspects of grave detection with resistivity surveys remain imperfectly understood. One such aspect is the effect of seasonal changes in climate on the resistivity response of graves. In this study, resistivity survey data collected over three years over ~~two~~ three simulated graves were analysed in order to assess how the graves' resistivity anomalies ~~vary~~ varied seasonally and when ~~surveys are~~

~~[1]Now at~~

~~optimal~~they could most easily be detected. Thresholds were used to identify anomalies, and the ‘residual volume’ of grave-related anomalies was calculated as the area bounded by the relevant thresholds multiplied by the anomaly’s average value above the threshold. The residual volume of a resistivity anomaly associated with a buried pig cadaver showed evidence of repeating annual patterns and was moderately correlated with the soil moisture budget. ~~Geophysical anomalies, associated with an animal cadaver, were easiest to detect between January to April~~This anomaly was easiest to detect between January and April each year, after prolonged periods of high net gain in soil moisture. The resistivity response of a wrapped cadaver was more complex,~~,~~ although it also showed evidence of seasonal variation during the third year after burial. We suggest that the observed variation in the graves' resistivity anomalies was caused by seasonal change in survey data noise levels, which was in turn influenced by the soil moisture budget. It is ~~suggested~~ possible that similar variations occur elsewhere ~~with~~ for sites with seasonal climate variations and this could affect successful detection of other subsurface features. Further research to investigate how different climates and soil types affect seasonal variation in grave-related resistivity anomalies would be useful.

Keywords

Near-surface geophysics; electrical resistivity; seasonal variation; forensic search; clandestine grave.

1. Introduction

Along with several other near-surface geophysical techniques (see e.g. Cheetham, 2005; Pringle et al., 2012a; Ruffel and McKinley 2005), electrical resistivity surveys have proven useful for detecting several different types of grave. To date, resistivity surveys have been used in searches for graves of archaeological interest (e.g. Ellwood et al., 1994), unmarked cemetery graves (Ellwood, 1990) and clandestine graves containing the remains of murder victims (Cheetham, 2005). From around 2000 onwards, there has been particular interest in the use of resistivity surveys for locating clandestine graves (e.g. Buck, 2003; Scott and Hunter, 2004; Pringle and Jervis, 2010). During the same period, several controlled experiments have been conducted in order to improve our understanding of how resistivity surveys can be used to detect this type of grave (e.g. Jervis et al., 2009a,b; Juerges et al., 2010; Powell, 2010; Pringle et al., 2008, 2012b,c). However, some ~~areas~~ aspects of grave detection with resistivity surveys remain incompletely understood. For example, the effects of soil type and seasonal changes in soil resistivity on the resistivity response of graves are not fully understood.

This study was conducted to investigate the effect of seasonal climatic changes on the ability of resistivity surveys to detect clandestine graves. There is evidence that changes in soil moisture content caused by seasonal weather patterns can affect the detection of clandestine graves with ground penetrating radar (Hammon et al., 2000; Schultz and Martin, 2012). Since soil resistivity is known to vary seasonally, it is possible that grave detection with resistivity surveys may be similarly affected.

1.1 Seasonal variation in resistivity data

Moisture content is one of the two main factors that affect the electrical conductivity of soil (the other being the conductivity of the water in the soil; Friedman, 2005). As such, seasonal changes in soil moisture content or the level of the water table ~~can~~ will cause seasonal variation in soil resistivity. Seasonal changes of approximately ±15% in soil resistivity relative to the annual average for a 500 m long profile have been reported (Aaltonen and Olofsson, 2002). Furthermore, seasonal patterns in soil conductivity have been shown to closely resemble the soil moisture budget (i.e. the net loss or gain in soil moisture content due to the combined effects of rainfall and evapotranspiration; Binley et al., 2002). In addition to affecting the bulk resistivity of the soil, seasonal climatic factors can influence the appearance and even detection of individual features in resistivity survey datasets. The resistivity anomalies associated with some infilled ~~ancient~~ archaeological defence ditches, for example, are easier to detect around the time of either the annual minimum or maximum (depending on the individual ditch) of the soil moisture budget (Clark, 1996). Al Chalabi and Rees (1962) found the 'average anomaly' (which they computed as the standard deviation of a resistivity profile) of one such ditch was inversely proportional to the soil moisture budget. Similarly, the resistivity anomalies of ~~ancient~~ archaeological graves at a cemetery in Garchy in France have been shown to be easiest to detect when the soil is relatively dry (Scollar et al., 1990). ~~Explanations offered for seasonal variation in the appearance of resistivity anomalies include: changes in~~

~~near-surface soil resistivity affecting the depth of investigation of the surveys; and~~Seasonal variation in the appearance of resistivity anomalies can be caused by differences between the moisture retention characteristics of the feature that causes~~d~~ the anomaly and those of the surrounding soil (Clark, 1996; Scollar et al., 1990). As such, different soil types and local geological conditions can influence the seasonal variation in a resistivity anomaly. For example, Clark (1996) found the seasonal variation in ditches at locations with chalk bedrock to be unusual compared to that observed at locations with different geologies. Another possible cause of seasonal variation in resistivity anomalies is change in the effective depth of resistivity measurements, which is caused by seasonal change in the resistivity of near-surface soils.

1.2 Background to this study

In this study, we used existing resistivity datasets that were collected at a test site where buried pig cadavers were used as a proxy for clandestine graves (Jervis et al., 2009b; Pringle et al., 2012c). We focussed on three~~two~~ of these test graves: one contained a pig cadaver, the second did not contain a cadaver, and the ~~other~~ third contained a pig cadaver wrapped in a porous tarpaulin made of woven polyethelene strands - we refer to these respectively as the 'pig grave', the ‘empty grave’ and the 'wrapped pig grave'. The pig grave was typically detected as a low resistivity anomaly, which was predominantly caused by electrically conductive fluid within the grave (Jervis et al., 2009b). This 'grave fluid' was most likely decomposition fluid mixed with soil water. The wrapped pig grave was primarily detected as a high resistivity anomaly, although low resistivity anomalies were occasionally present around the edges of the grave (Pringle et al., 2012c). The high resistivity anomaly was probably caused by the tarpaulin-wrapped cadaver acting as a barrier to the flow of electrical current in the ground. The low resistivity anomalies may have been caused by grave fluid that had leaked through the weave of the tarpaulin. Alternatively, these anomalies may have been caused by a pool of percolating soil-water that had become trapped on the uppermost side of the tarpaulin. No obvious anomaly was observed for the empty grave (Jervis et al., 2009b; Pringle et al., 2012c).

The resistivity datasets of Pringle et al. (2012c) are particularly useful for studying seasonal variation because they cover three years. As such, seasonal variation should be evident as annually repeating patterns in the data. Pringle et al. did observe that the graves were easiest to detect around the time of "winter to mid-spring" (Fig. 1) and suggested this was because the noise levels in the resistivity data were lowest at this time. Jervis (2010) studied variation in the resistivity responses of these graves during the first year after burial and found that characteristic properties of the pig grave anomaly were moderately correlated with the soil moisture budget. In this study, Jervis's methods are developed and applied to the three years'– datasets collected by Pringle et al. The primary aim was to gain a better understanding of the nature and causes of the seasonal variation in the graves' resistivity anomalies.

2. Methods

Because the study site and methods of data collection and processing have already been described elsewhere (Jervis, 2010; Jervis et al., 2009b; Pringle et al., 2012c), only a brief summary is provided here. Instead the focus in this section~~here~~ is on the methods used to identify and study seasonal patterns in the resistivity responses of the graves.

2.1 Study site and simulated graves

The site of the experimental work was an area of former garden land on the campus of Keele University in Staffordshire in the UK. The soil at the site was predominantly sandy loam, with fragments of the shallow sandstone bedrock present at about 0.5 m below ground level. It was judged to be a semi-rural environment. The empty grave was created on the 6th of December, 2007, and the pig grave and the wrapped pig grave~~two graves that we focussed on in this study~~ were created on the 7th of December, 2007. ~~Both~~ All three graves were 0.5 m deep. The empty grave contained only backfilled soil, and the pig grave and the wrapped pig grave both contained a pig cadaver that weighed approximately 80 kg. The cadaver in the wrapped pig grave ~~is~~ was wrapped in a tarpaulin made of woven polyethelene strands (see Jervis et al., 2009b).

2.2 Resistivity survey data collection and processing

Each resistivity survey dataset consisted of measurements made 0.25 m by 0.25 m apart using a twin probe array with a mobile electrode separation of 0.5 m. The array's reference electrodes were placed 1 m apart at ~~the same~~a position that was ~~at a distance of~~ 17 m from the survey area. The datasets used here were collected between the 4th of January, 2008 and the 3rd of December, 2010, which was 28 to 1092 days after burial. These datasets were collected every 28 days up to 728 days after burial and approximately every 30 days from 794 to 1092 days after burial.

During data processing, the values in each ~~digital~~ dataset ~~was~~ were converted from resistance to resistivity by multiplication by an appropriate geomtric factor (see e.g. Reynolds, 2011). For the electrode arrangement described above, the geometric factor was $34\pi/49$. The resistivity datasets were then de-spiked ~~(to remove anomalous data points)~~by visually identifying and removing isolated outliers, and interpolated to a cell size of 0.125 m by 0.125 m to aid visual interpretation. Each dataset was subsequently ~~and then~~ de-trended by the fitting and removal of a third order polynomial surface. Each processed dataset was then normalised by dividing its values by the dataset's standard deviation. As a result of trend removal and normalisation, respectively, each dataset had a mean of zero and a standard deviation of one. This made it straight forward to make comparisons between datasets.

2.3 Analysis of the raw survey data

It was important to identify seasonal variation in the raw resistivity data in order to help understand whether this affected the resistivity responses of the graves. The average and the standard deviation of the raw datasets after de-spiking ~~was~~ were calculated and results analysed for seasonal patterns ~~(see Fig. 1)~~. The standard deviation values were ~~taken to represent~~ used as a measure of the noise levels in the respective survey datasets.

2.4 Identification and analysis of grave-related anomalies

In studying the grave-related anomalies, ~~two~~ sub-areas measuring 2.5 m by 1.75 m around each of the ~~two~~ three graves were identified (Fig. 2a). These areas included borders of approximately 0.5 m around the edges of the graves because low resistivity anomalies that appeared to be grave-related ~~often~~ extended beyond the graves' surface outlines. These anomalies were most probably caused by the seeping of grave fluid into the soil around the graves. Any values within these areas that were above +2 SD or below -2 SD were respectively classed as high or low resistivity grave-related anomalies. The thresholds of ±2 SD were chosen to be low enough to include features thought to be caused by the graves, but high enough to exclude most of the noise in the data.

To study variation in the graves resistivity responses, it was necessary to obtain a value that summarised how well each grave was detected. To do this, the ‘volume’ bounded by the surface of each grave's anomaly and the threshold was calculated (Fig. 2b). This quantity was equal to the area bounded by the relevant threshold multiplied by the average residual value of the anomaly, which we define as the difference between the anomaly's average value and the threshold. Technically, this was not a volume, since it was the product of a normalised value ~~that had no units~~(measured in standard deviations) and an area. As such, we shall refer to this quantity, which had units of $m^2 \cdot SD$, as an anomaly's 'residual volume.~~Consequently, chosen volume values had the slightly counter-intuitive units of m^2, but this 'volume' was the most satisfactory term for this quantity.~~ The residual volume ~~estimate~~ reflected both the size of an anomaly and by how much it exceeded the relevant threshold. Both of these properties were considered useful indicators of how well the grave was detected, since a large anomaly that greatly exceeded the threshold value would be easy to identify.

2.5 Calculation of the soil moisture budget

The soil moisture budget was calculated in order to assess whether it influenced the grave-related anomalies' residual volumes. Weather data was obtained from Keele University's weather station, which was located about 200 m ~~in distance~~ from the experimental site. During the study period, monthly rainfall ranged from 21.6 mm to 166.7 mm and the average monthly temperature ranged from -1.2°C to 15.8°C. The weather data and a modified version of Thornthwaite's (1948) method were~~was~~ used to calculate soil moisture budgets for periods of 30 to 210 days. First, monthly evapotranspiration values were calculated following Thornthwaite's method. These values were then divided by the number of days in the month and multiplied by 30 to give 30-day evapotranspiration estimates. These values were taken to represent the evapotranspiration during the 30 days to the end of each month. The estimated evapotranspiration followed a reasonably smooth annual pattern (with peaks around July and lows around February), and these values were interpolated to give a 30-day evapotranspiration value for every day of the project. Each evapotranspiration value was subtracted from the total rainfall in the same 30-day period to give 30-day soil moisture budget estimates. Moisture budgets for periods of 60, 90, 120, 150, 180 and 210 days were calculated by summing moisture budgets for consecutive 30 day periods. Soil moisture budgets for the periods up to the end of the day before each survey were then used for comparison with the anomalies' residual volumes (Fig. 3).

2.6 Regression analysis

Regression analysis (with least squares fitting) was used to estimate linear relationships between the anomalies' residual volumes, the soil moisture budgets, and the properties (i.e. the average and standard deviation) of the raw survey data. In calculating these relationships, the reciprocals of the raw datasets' properties were used, because resistivity values and their standard deviations have both been shown to be inversely proportional to the soil moisture budget (e.g. Al Chalabi and Rees, 1962; Binley et al., 2002).

3. Results

3.1 The raw resistivity data

The general pattern in the standard deviation of the raw resistivity datasets was one of relatively low values in the early part of each year followed by much higher values later on (Fig. 4). The standard deviation was reasonably constant at around 11 Ω·m between January and April, after which it increased until September and then decreased back towards 11 Ω·m. The average resistivity did not follow quite such an obvious pattern as the standard deviation. However, some peaks in the average resistivity occurred at approximately the same time as those in the standard deviation data.

The inverse of the raw datasets' standard deviation was moderately correlated ($R^2>0.5$) with the soil moisture budgets calculated for periods of 90 to 210 days (Fig. 5). The closest correlation was 0.77, and this was for the relationship with the 150-day soil moisture budget. The inverse of the average resistivity was not well correlated ($R^2<0.3$) with any of the soil moisture budgets calculated for this study.

3.2 The empty grave

The empty grave was associated with a high resistivity anomaly (Fig. 6). This anomaly was absent for most of 2008, and its residual volume was less than 0.1 m^2·SD even when it was present. In 2009, the anomaly was present more often and its residual volume was slightly higher. There was a peak in the anomaly’s residual volume between April and October, and its maximum value was 0.19 $m^2 \cdot SD$. The anomaly’s residual volume was higher still in 2010, with a maximum value of 0.82 $m^2 \cdot SD$. There was a peak in the anomaly’s residual volume between April and the end of the year. The residual volume of the empty grave’s anomaly was not well correlated ($R^2<0.3$) with any of the soil moisture budgets. Similarly, the anomaly’s residual volume was not well correlated with the inverse values of the average or the standard deviation of the raw datasets.

3.~~2~~ 3 The pig grave

The residual volume of the pig grave's low resistivity anomaly varied noticeably during the study period (Fig. ~~6~~7). The anomaly's residual volume increased from the start of the study until April 2008, when it reached its maximum value of 2.7 $m^2 \cdot SD$, before decreasing down to ~0.5 $m^2 \cdot SD$. Further peaks in its residual volume followed in late-2008/early-2009 and late-2009/early-2010. The anomaly's residual volume was much smaller between these peaks and its lowest value, which occurred in August 2009, ~~(~~was ~0.04 $m^2 \cdot SD$~~)~~.

The peaks in the anomaly's residual volume all occurred at around the same time of year, which was approximately between November and May. These peaks became smaller and shorter-lived in each successive year. The relative lows in the anomaly's residual volume all lasted roughly from June to October and each low lasted longer than its predecessor.

The anomaly’s residual volume was moderately correlated with the 150-day and 180-day soil moisture budgets (R^2=0.57 and R^2=0.59 respectively; Fig. 8~~7~~). The residual volume was also moderately correlated with the inverse of the raw datasets' standard deviation (R^2=0.53).

No high resistivity anomalies were identified for the pig grave at the +2 SD threshold.

3.~~3~~4 The wrapped pig grave

The residual volumes of both the high and low resistivity anomalies associated with the wrapped pig grave varied throughout the study period (Fig. 9~~8~~). The high resistivity anomaly's residual volume was usually larger than that of the low resistivity anomaly, but both anomalies' residual volumes were zero on several occasions. The peaks in the high and low resistivity anomalies' residual volumes appeared to alternate: the low resistivity peaks occurred midway between the main high resistivity peaks, and vice versa.

The high resistivity anomaly's residual volume was relatively large, at 0.5 $m^2 \cdot SD$, shortly after burial. Its residual volume subsequently decreased until it reached zero in May 2008. In 2009, the anomaly's residual volume recovered somewhat and there was a small peak of 0.15 $m^2 \cdot SD$ in April. In 2010, the anomaly's residual volume was larger and its peak value in that year also occurred in April (0.54 $m^2 \cdot SD$).

The low resistivity anomaly was not present for much of the study. There were brief peaks in this anomaly's residual volume in around October in all three years of the study, but these peaks did not exceed 0.02 $m^2 \cdot SD$.

The residual volumes of the grave's high and low resistivity anomalies were not well correlated (R^2<0.3) with either the inverse of the averages or the standard deviations of the raw datasets, or indeed any of the soil moisture budgets.

4. Discussion

The results of this study showed evidence of seasonal electrical resistivity ~~survey~~ variations ~~of the same target~~ as annually repeating patterns in the properties of the raw datasets and the resistivity responses of the graves.

From reviewing the datasets collected, it may seem surprising that the standard deviation of the raw datasets ~~were~~ was more closely related than the average resistivity to the soil moisture budget. However, the wide separation between the mobile and the reference electrodes means that relatively deep soil between the electrode pairs influences resistivity measurements made with the twin probe array. The resistivity of this deeper soil would be much more stable than that of the near-surface soils, which may explain why the average resistivity measured in this study does not exhibit much seasonal variation. The variation in resistivity measurements made with the twin probe array comes from the movement of the mobile electrodes between each measurement. The closely-spaced mobile electrodes are more sensitive to near surface changes in resistivity, and the resistivity of this near surface soil is more likely to vary seasonally (see Reynolds, 2011). This may explain why the standard deviation of the raw resistivity datasets exhibited a seasonal pattern and was well correlated with the soil moisture budget. So even if there is no variation in the resistivity response of a target feature, there may be certain times of the year that are best for resistivity surveys because of variation in the noise levels. In this study, the noise levels were lowest in collected datasets between approximately January and April of each year.

The exact reason for the correlation between the standard deviation and the soil moisture budget is not clear. One possibility is that the resistivity of the near surface soil was relatively homogeneous when the soil was wet, but natural heterogeneities became more pronounced as the soil dried out. ~~Alternatively, higher soil resistivity during dry periods may have restricted the depth of investigation of the resistivity surveys to more heterogeneous soil nearer the ground surface.~~

Although disturbed soil is usually expected to cause low resistivity anomalies, the empty grave in this study was associated with a high resistivity anomaly. This anomaly was not particularly noticeable during the first two years of the study, but it was more obvious in the third year. The year on year increase in this anomaly's residual volume could have been caused by the gradual drying out of the grave soil in dry weather. This explanation is consistent with the fact that the annual peaks in the anomaly's residual volume occurred in the summer months when the 30-day soil moisture budget was typically negative. It seems likely that disturbing the soil to create the grave affected the soil's ability to retain moisture.

There may have been some seasonal variation in the empty grave's residual volume, even though it was not well correlated with the soil moisture budget. The rise and fall in the anomaly's residual volume in 2010 could have been the beginning of an annual pattern. The 2010 peak in the anomaly's residual volume occurred when the 30-, 60- and 90-day soil moisture budgets were negative. The grave's resistivity could, therefore, have been a result of seasonal wetting and drying of the grave soil that was a result of changes in the short-term soil moisture budget.

The pattern in the residual volume of the pig grave's anomaly was ~~also~~ suggestive of seasonal variation because it was broadly similar in each year of the study. This variation was large enough to determine whether the grave could be detected: when its residual volume was low, the anomaly was difficult to identify in the resistivity data (Fig. 1 cf. Fig. 7~~6~~). The anomaly's residual volume was inversely proportional to the raw datasets' standard deviation, which suggests the noise levels in the survey data affected the anomaly's appearance. The anomaly itself may have been relatively constant while being alternately obscured when the data was noisy and revealed when the data was less noisy. In terms of the signal-to-noise ratio, therefore, it is suggested that it was the noise and not the signal that varied seasonally. If the soil moisture budget did cause the variation in the resistivity data's noise levels, it would also have been the ultimate cause of the seasonal variation in the pig grave anomaly's residual volume.

Some features in the residual volume of the pig grave anomaly did not appear to be part of a seasonal pattern. The prolonged initial increase in the anomaly's residual volume, for example, was not repeated in the later years of the project. This increase could be attributed to the accumulation of grave fluid in the soil during the most active phase of the cadaver's decomposition (see Pringle et al. 2012a). Another pattern that did not appear to be seasonal was the decrease in the maximum residual volume of the anomaly in each successive year of the project. This could have been caused by a gradual drainage of grave fluid to a depth at which it could no longer be detected. Another possibility is that the grave soil gradually dried out (as we suggest happened in the empty grave), and the corresponding rise in soil resistivity counteracted the low resistivity effect of the grave fluid. So, as well as seasonal factors, internal processes occurring within the grave may well have influenced its anomaly's residual volume. However, the correlation of 0.59 suggests that the soil moisture budget can explain more than half the variation in the pig grave anomaly's residual volume. The majority of the variation in this anomaly's residual volume during the project may, therefore, have been seasonal.

The evidence for seasonal patterns in the residual volume of the wrapped pig grave's anomalies was less clear. The high resistivity anomaly was the grave's main anomaly because it was detected more often and was typically larger in residual volume than the low resistivity anomaly. The patterns in the high resistivity anomaly's residual volume were primarily decline in 2008 and recovery in 2010. These patterns can be explained by the same processes of accumulation and, subsequently, drainage of grave fluid that is suggested to have happened within the pig grave. The accumulation of grave fluid, which could have counteracted the high resistivity effect of the tarpaulin-wrapped cadaver, could have caused the rapid decline in the anomaly's residual volume shortly after burial. Equally, the recovery in residual volume in 2010 could have been a result of the grave fluid's draining away. Alternatively, as with the empty grave, the increase in the high resistivity anomaly's residual volume towards the end of the study could have been caused by the grave soil's drying out. The variation in the anomaly's residual volume in 2010 may also have been partly seasonal. The pattern of increasing residual volume up to a peak in April followed by decline throughout the rest of the year was similar to (although not the same as) the seasonal pattern in the pig grave anomaly's residual volume. Furthermore, although the high resistivity anomaly's residual volume was much smaller in 2009 than in 2010, the general patterns in both years were similar. Perhaps the grave fluid in the wrapped pig grave began to drain in 2009, which lead to a decrease in the interaction between the high and low resistivity anomalies. Seasonal variation in the resistivity data's noise levels could then have started to affect the high resistivity anomaly's residual volume. By the time more fluid had drained away in 2010, seasonal variation in the anomaly's residual volume could have become more pronounced.

The residual volume of the low resistivity anomaly associated with the wrapped pig grave also seemed to follow a seasonal pattern because it peaked at about the same time each year. Unlike the pig grave's low resistivity anomaly, the wrapped pig grave anomaly's residual volume peaked around the time of highs in the raw datasets' standard deviation. It therefore seems unlikely that the residual volume of the wrapped pig grave's low resistivity anomaly was related to the resistivity data's noise levels: it was unlikely that the anomaly would be easiest to detect when the data was noisiest. The anomaly's residual volume may instead have been directly related to the soil moisture budget. The peaks in the low resistivity anomaly's residual volume occurred during lows in the 180-day soil moisture budget. When the soil was particularly dry, hydraulic gradients may have drawn the grave fluid through the weave of the tarpaulin and into the surrounding soil where it could more easily be detected.

In terms of variation in the anomalies, it was perhaps the pig grave anomaly and the wrapped pig grave's high resistivity anomaly that had most in common. Both anomalies may, to a greater or lesser degree, have been affected by the accumulation and drainage of grave fluid and by seasonal factors. It is suggested that the seasonal variation in these anomalies ~~were~~ was caused by variation in the resistivity datasets' noise levels, which was in turn caused by the seasonal soil moisture budget. This is quite different to the causes of seasonal variation that have been suggested by others (e.g. see ~~Binley et al. 2002~~Clark, 1996). Furthermore, the fact that some resistivity anomalies are easiest to detect when the soil moisture budget is negative suggests that the seasonal variation they exhibit is different to that observed here. This is perhaps not too surprising, since the results for both wrapped pig grave anomalies suggest that internal changes within a detectable subsurface feature can override seasonal variation related to fluctuating noise levels in resistivity data. Thus, it seems there may be two types of seasonal variation: that related to direct interaction between a subsurface feature and the soil moisture budget, and that related to variation in the noise levels of resistivity data (which may itself be governed by the soil moisture budget).

5. Conclusions

This study results show that seasonal weather patterns can affect the ability of resistivity surveys to detect clandestine graves. Based on the results for the pig grave, it seems that the best conditions for locating recent burials occur around the time of the annual maximum in the 180-day soil moisture budget, which in this study was between January and~~to~~ April each year.

It is suggested that the changing soil moisture budget caused seasonal variation in the resistivity data's noise levels, which in turn caused variation in the pig grave's resistivity anomaly. However, for much of the study, the wrapped pig grave's high and low resistivity anomalies seemed to be relatively unaffected by this variation. It seems that internal changes (related to the fluid that was partially trapped in the tarpaulin) within the grave were the primary cause of variation in its resistivity anomalies. These internal changes may, therefore, have obscured any effect that seasonal variation in the resistivity data's noise levels may have had on the grave's anomalies. Towards the end of the study there was some evidence of noise-related seasonal variation in the high resistivity anomaly's residual volume.

Seasonal variation in the grave-related anomalies that was caused by variation in the resistivity data's noise levels would be unrelated to processes occurring within the graves. This type of variation could affect the detection of other types of subsurface feature, as long as there was no major internal variation within the feature that affected its resistivity.

There could, therefore, be times of the year that provide the best conditions for resistivity surveys because the noise levels in the resulting data will be low. Since the standard deviation of our datasets was moderately correlated with the soil moisture budget, it would be possible to use existing weather data to predict when the best conditions occur. However, seasonal variation in the noise levels in resistivity data may be different for climates and soil types that are different to those present at our study location. As such, we recommend further research be conducted to study the effect of local climate on the detection of graves and other features in a range of environments.

Acknowledgements

Jamie Hansen (a PhD student at Keele University) is thanked for assistance with data collection. Two open source software packages were particularly useful for this project: Generic Mapping Tools (GMT) software was used to analyse the resistivity data and prepare figures, and R software to perform regression analysis. This study was partially based on the lead author's PhD research, which was funded by the EPSRC and RSK Stats Ltd. ~~Neither of these funding sources had any involvement in this research.~~ The comments of two anonymous reviewers helped to improve this paper.

References

Aaltonen, J., Olofsson, B., 2002. Direct current (DC) resistivity measurements in long-term groundwater monitoring programs. Environ. Geol. 41, 662-671. DOI:10.1007/s00254-001-0447-1

Al Chalabi, M.M., Rees, A.I., 1962. An experiment on the effect of rainfall on electrical resistivity anomalies in the near surface. Bonn. Jahrb. 162, 266-271.

Binley, A., Winship, P., West, L.J., Pokar, M., Middleton, R., 2002. Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles. J. Hydrol. 267, 160-172. DOI:10.1016/S0022-1694(02)00147-6

Buck, S.C., 2003. Searching for graves using geophysical technology: field tests with ground penetrating radar, magnetometry and electrical resistivity. J. Forensic Sci. 48, 1-7. DOI:10.1520/JFS2002165

Cheetham, P., 2005. Forensic geophysical survey, in: Hunter, J., Cox, M. (Eds.), Forensic Archaeology: Advances in Theory and Practice. Routledge, Oxon, pp. 62-95. ISBN:0415273129

Clark, A.J., 1996. Seeing Beneath the Soil: Prospecting Methods in Archaeology, first rev. ed. Batsford Ltd., London. ISBN:0415214408

Ellwood, B.B., 1990. Electrical resistivity surveys in two historical cemeteries in northeast Texas: a method for delineating unidentified burial shafts. Hist. Archaeol. 24, 91-98. ISSN:0440-9213

Ellwood, B.B., Owsley, D.W., Ellwood, S.H., Mercado-Allinger, P.A., 1994. Search for the grave of the hanged Texas gunfighter, William Preston Longley. Hist. Archaeol. 28, 94-112. ISSN:0440-9213

Friedman, S.P., 2005. Soil properties influencing apparent electrical conductivity: a review. Comput. Electron. Agric. 46, 45-70. DOI:10.1016/j.compag.2004.11.001

Hammon, W.S., McMechan, G.A., Zeng, X., 2000. Forensic GPR: finite-difference simulations of responses from buried human remains. J. Appl. Geophys. 45, 171-186. DOI:10.1016/S0926-9851(00)00027-6

Jervis, J.R., 2010. The detection of clandestine graves using electrical resistivity surveys: results from controlled experiments and a case study. Unpublished PhD thesis, Keele University.

Jervis, J.R., Pringle, J.K., Cassella, J.P., Tuckwell, G., 2009a. Using soil and groundwater data to understand resistivity surveys over a simulated clandestine grave, in: Ritz, K., Dawson, L., Miller, D. (Eds.), Criminal and Environmental Soil Forensics. Springer

Science+Business Media B.V., Dordrecht, pp. 271-284. ISBN:978-1-4020-9203-9

Jervis, J.R., Pringle, J.K., Tuckwell, G.W., 2009b. Time-lapse resistivity surveys over simulated clandestine graves. Forensic Sci. Int. 192, 7-13. DOI:10.1016/j.forsciint.2009.07.001

Juerges, A., Pringle, J.K., Jervis, J.R., Masters, P., 2010. Comparisons of magnetic and electrical resistivity surveys over simulated clandestine graves in contrasting burial environments. Near Surf. Geophys. 8, 529-539. DOI:10.3997/1873-0604.2010042

Powell, K., 2010. Grave Concerns: Locating and Unearthing Human Bodies. Australian Academic Press, Bowen Hills. ISBN:1921513705

Pringle, J.K., Jervis, J.R., 2010. Electrical resistivity survey to search for a recent clandestine burial of a homicide victim, UK. Forensic Sci. Int. 202, e1-e7. DOI:10.1016/j.forsciint.2010.04.023

Pringle, J.K., Ruffell, A., Jervis, J.R., Donnelly, L., McKinley, J., Hansen, J., Morgan, R., Pirrie, D., Harrison, M., 2012a. The use of geoscience methods for terrestrial forensic searches. Earth-Sci. Rev. 114, 108-123. DOI:10.1016/j.earscirev.2012.05.006

Pringle, J.K., Holland, C., Skornik, K., Harrison, M., 2012b. Establishing forensic search methodologies and geophysical surveying for the detection of clandestine graves in coastal beach environments. Forensic Sci. Int. 219, e29-e36. DOI:10.1016/j.forsciint.2012.01.010

Pringle, J.K., Jervis, J.R., Hansen, J.D., Jones, G.M., Cassidy, N.J., Cassella, J.P., 2012c. Geophysical monitoring of simulated clandestine graves using electrical and ground-penetrating radar methods: 0-3 years after burial. J. Forensic Sci. 57, 1467-1486. DOI:10.1111/j.1556-4029.2012.02151.x

Pringle, J.K., Jervis, J.R., Cassella, J.P., Cassidy, N.J., 2008. Time-lapse geophysical investigations over a simulated urban clandestine grave. J. Forensic Sci. 53, 1405-1416. DOI:10.1111/j.1556-4029.2008.00884.x

Reynolds, J.M., 2011. An Introduction to Applied and Environmental Geophysics, 2nd review edition. John Wiley and Sons. Chichester. ISBN: 0471485365

Ruffell, A., McKinley, J., 2005. Forensic geoscience: applications of geology, geomorphology and geophysics to criminal investigations. Earth-Sci. Rev. 69, 235-247. DOI:10.1016/j.earscirev.2004.08.002

Schultz, J.J., Martin, M.M.., 2012. Monitoring controlled graves representing common burial scenarios with ground penetrating radar. J. Appl. Geophys. 83, 74-89. DOI:10.1016/j.jappgeo.2012.05.006

Scollar, I., Tabbagh, A., Hesse, A., Herzog, I., 1990. Archaeological Prospecting and

Remote Sensing. Cambridge University Press, Cambridge. ISBN: 0521115469

Scott, J., Hunter, J.R., 2004. Environmental influences on resistivity mapping for the location of clandestine graves, in: Pye, K., Croft, D.J. (Eds.), Forensic geoscience: principles, techniques and applications. Geological Society, London, pp. 33-38. ISBN: 1862391610

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55-94. Stable URL: http://www.jstor.org/stable/210739 Last Access: 15/12/2013.

Figure captions

Figure 1: Example processed resistivity survey datasets, showing the resistivity responses of the ~~two~~ three graves (a) in late summer (August 2009), and (b) in early spring (March 2010), and demonstrating the seasonal variation in the data. Common scale is standard deviation. The grave corners are indicated by white circles with black centres; the pig grave is on the left side of the figure, the empty grave is in the centre, and the wrapped pig grave is on the right. After Jervis et al. (2009b) and Pringle et al. (2012c).

Figure 2: An illustration of how the grave-related anomalies were identified and their residual volumes were calculated. (a) An example dataset showing the chosen areas for the pig grave, the empty grave, and the wrapped pig grave (dashed black rectangles) and the -2 (solid white lines) and +2 (solid black lines) SD thresholds respectively. (b) A three-dimensional representation of the data that exceeded the +2 threshold within the area chosen for the wrapped pig grave. The residual volume of this anomaly was calculated as that bounded by the surface of this shape and the plane of the +2 SD threshold.

Figure 3: Three of the soil moisture budgets (abbreviated as ‘S.M.B.’ on the vertical axis) used in this study. The moisture budgets are typically positive in the early part of each year (especially January to June) and negative in the latter part of the year (July to November). This pattern becomes more pronounced as the period over which the moisture budget is calculated increases.

Figure 4: The average (plotted against the left axis) and the standard deviation (plotted

against the right axis) of the raw resistivity survey datasets. After Pringle et al. (2012c).

Figure 5: The relationship between the inverse of the standard deviation of the raw resistivity datasets and the soil moisture budget. (a) Correlation as a function of the soil moisture budget period. (b) Relationship between the inverse of the standard deviation and the 150-day soil moisture budget. The equation for the estimated regression relationship (dashed line) is shown at the top.

Figure 6: The residual volume of the empty grave anomaly. Asterisks indicate values calculated from the two datasets shown in Fig. 1.

Figure 7~~6~~: The residual volume of the pig grave anomaly. Asterisks indicate values calculated from the two datasets shown in Fig. 1.

Figure 8~~7~~: Relationships between the pig grave anomaly's residual volume and the soil moisture budget. (a) Correlation as a function of the soil moisture budget period. (b) Relationship between the anomaly's residual volume and the 180-day soil moisture budget. The equation for the estimated regression relationship (dashed line) is shown at the top.

Figure 9~~8~~: The residual volume of the high resistivity (plotted against the left axis) and low resistivity (plotted against the right axis) wrapped pig grave anomalies. Asterisks indicate values calculated from the two datasets shown in Fig. 1.

A study of the effect of seasonal climatic factors on the electrical resistivity response of three experimental graves

John R. Jervis[a], Jamie K. Pringle[a,]*

[a]School of Physical Sciences and Geography, Keele University, Keele, Staffordshire, ST5 5BG, UK.

*Corresponding author. Tel.: +44 1782 733163.

E-mail addresses: j.jervis@keele.ac.uk (J. Jervis), j.k.pringle@keele.ac.uk (J. Pringle).

Abstract

Electrical resistivity surveys have proven useful for locating clandestine graves in a number of forensic searches. However, some aspects of grave detection with resistivity surveys remain imperfectly understood. One such aspect is the effect of seasonal changes in climate on the resistivity response of graves. In this study, resistivity survey data collected over three years over three simulated graves were analysed in order to assess how the graves' resistivity anomalies varied seasonally and when they could most easily be detected. Thresholds were used to identify anomalies, and the 'residual volume' of grave-related anomalies was calculated as the area bounded by the relevant thresholds multiplied by the anomaly's average value above the threshold. The residual volume of a resistivity anomaly associated with a buried pig cadaver showed evidence of repeating annual patterns and was moderately correlated with the soil moisture budget. This anomaly was easiest to detect between January and April each year, after prolonged periods of high net gain in soil moisture. The resistivity response of a wrapped cadaver was more complex, although it also showed evidence of seasonal variation during the third year after burial. We suggest that the observed variation in the graves' resistivity anomalies was caused by seasonal change in survey data noise levels, which was in turn influenced by the soil moisture budget. It is possible that similar variations occur elsewhere for sites with seasonal climate variations and this could affect successful detection of other subsurface features. Further research to investigate how different climates and soil types affect seasonal variation in grave-related resistivity anomalies would be useful.

Keywords

Near-surface geophysics; electrical resistivity; seasonal variation; forensic search; clandestine grave.

1. Introduction

Along with several other near-surface geophysical techniques (see e.g. Cheetham, 2005; Pringle et al., 2012a; Ruffel and McKinley 2005), electrical resistivity surveys have proven useful for detecting several different types of grave. To date, resistivity surveys have been used in searches for graves of archaeological interest (e.g. Ellwood et al., 1994), unmarked cemetery graves (Ellwood, 1990) and clandestine graves containing the remains of murder victims (Cheetham, 2005). From around 2000 onwards, there has been particular interest in the use of resistivity surveys for locating clandestine graves (e.g. Buck, 2003; Scott and Hunter, 2004; Pringle and Jervis, 2010). During the same period, several controlled experiments have been conducted in order to improve our understanding of how resistivity surveys can be used to detect this type of grave (e.g. Jervis et al., 2009a,b; Juerges et al., 2010; Powell, 2010; Pringle et al., 2008, 2012b,c). However, some aspects of grave detection with resistivity surveys remain incompletely understood. For example, the effects of soil type and seasonal changes in soil resistivity on the resistivity response of graves are not fully understood.

This study was conducted to investigate the effect of seasonal climatic changes on the ability of resistivity surveys to detect clandestine graves. There is evidence that changes in soil moisture content caused by seasonal weather patterns can affect the detection of clandestine graves with ground penetrating radar (Hammon et al., 2000; Schultz and Martin, 2012). Since soil resistivity is known to vary seasonally, it is possible that grave detection with resistivity surveys may be similarly affected.

1.1 Seasonal variation in resistivity data

Moisture content is one of the two main factors that affect the electrical conductivity of soil (the other being the conductivity of the water in the soil; Friedman, 2005). As such, seasonal changes in soil moisture content or the level of the water table will cause seasonal variation in soil resistivity. Seasonal changes of approximately ±15% in soil resistivity relative to the annual average for a 500 m long profile have been reported (Aaltonen and Olofsson, 2002). Furthermore, seasonal patterns in soil conductivity have been shown to closely resemble the soil moisture budget (i.e. the net loss or gain in soil moisture content due to the combined effects of rainfall and evapotranspiration; Binley et al., 2002). In addition to affecting the bulk resistivity of the soil, seasonal climatic factors can influence the appearance and even detection of individual features in resistivity survey datasets. The resistivity anomalies associated with some infilled archaeological defence ditches, for example, are easier to detect around the time of either the annual minimum or maximum (depending on the individual ditch) of the soil moisture budget (Clark, 1996). Al Chalabi and Rees (1962) found the 'average anomaly' (which they computed as the standard deviation of a resistivity profile) of one such ditch was inversely proportional to the soil moisture budget. Similarly, the resistivity anomalies of archaeological graves at a cemetery in Garchy in France have been shown to be easiest to detect when the soil is relatively dry (Scollar et al., 1990). Seasonal variation in the appearance of resistivity anomalies can be caused by differences between the moisture retention characteristics of the feature that causes the anomaly and those of the surrounding soil (Clark, 1996; Scollar et al., 1990). As such, different soil types and local geological conditions can influence the seasonal variation in a resistivity anomaly. For example, Clark (1996) found the seasonal variation in ditches at locations with chalk bedrock to be unusual compared to that observed at locations with different geologies. Another possible cause of seasonal variation in resistivity anomalies is change in the effective depth of resistivity measurements, which is caused by seasonal change in the resistivity of near-surface soils.

1.2 Background to this study

In this study, we used existing resistivity datasets that were collected at a test site where buried pig cadavers were used as a proxy for clandestine graves (Jervis et al., 2009b; Pringle et al., 2012c). We focussed on three of these test graves: one contained a pig cadaver, the second did not contain a cadaver, and the third contained a pig cadaver wrapped in a porous tarpaulin made of woven polyethelene strands - we refer to these respectively as the 'pig grave', the ‘empty grave’ and the 'wrapped pig grave'. The pig grave was typically detected as a low resistivity anomaly, which was predominantly caused by electrically conductive fluid within the grave (Jervis et al., 2009b). This 'grave fluid' was most likely decomposition fluid mixed with soil water. The wrapped pig grave was primarily detected as a high resistivity anomaly, although low resistivity anomalies were occasionally present around the edges of the grave (Pringle et al., 2012c). The high resistivity anomaly was probably caused by the tarpaulin-wrapped cadaver acting as a barrier to the flow of electrical current in the ground. The low resistivity anomalies may have been caused by grave fluid that had leaked through the weave of the tarpaulin.

Alternatively, these anomalies may have been caused by a pool of percolating soil-water that had become trapped on the uppermost side of the tarpaulin. No obvious anomaly was observed for the empty grave (Jervis et al., 2009b; Pringle et al., 2012c).

The resistivity datasets of Pringle et al. (2012c) are particularly useful for studying seasonal variation because they cover three years. As such, seasonal variation should be evident as annually repeating patterns in the data. Pringle et al. did observe that the graves were easiest to detect around the time of "winter to mid-spring" (Fig. 1) and suggested this was because the noise levels in the resistivity data were lowest at this time. Jervis (2010) studied variation in the resistivity responses of these graves during the first year after burial and found that characteristic properties of the pig grave anomaly were moderately correlated with the soil moisture budget. In this study, Jervis's methods are developed and applied to the three years' datasets collected by Pringle et al. The primary aim was to gain a better understanding of the nature and causes of the seasonal variation in the graves' resistivity anomalies.

2. Methods

Because the study site and methods of data collection and processing have already been described elsewhere (Jervis, 2010; Jervis et al., 2009b; Pringle et al., 2012c), only a brief summary is provided here. Instead the focus in this section is on the methods used to identify and study seasonal patterns in the resistivity responses of the graves.

2.1 Study site and simulated graves

The site of the experimental work was an area of former garden land on the campus of Keele University in Staffordshire in the UK. The soil at the site was predominantly sandy loam, with fragments of the shallow sandstone bedrock present at about 0.5 m below ground level. It was judged to be a semi-rural environment. The empty grave was created on the 6th of December, 2007, and the pig grave and the wrapped pig grave were created on the 7th of December, 2007. All three graves were 0.5 m deep. The empty grave contained only backfilled soil, and the pig grave and the wrapped pig grave both contained a pig cadaver that weighed approximately 80 kg. The cadaver in the wrapped pig grave was wrapped in a tarpaulin made of woven polyethelene strands (see Jervis et al., 2009b).

2.2 Resistivity survey data collection and processing

Each resistivity survey dataset consisted of measurements made 0.25 m by 0.25 m apart using a twin probe array with a mobile electrode separation of 0.5 m. The array’s reference electrodes were placed 1 m apart at a position that was 17 m from the survey area. The datasets used here were collected between the 4th of January, 2008 and the 3rd of December, 2010, which was 28 to 1092 days after burial. These datasets were collected every 28 days up to 728 days after burial and approximately every 30 days from 794 to 1092 days after burial.

During data processing, the values in each dataset were converted from resistance to resistivity by multiplication by an appropriate geomtric factor (see e.g. Reynolds, 2011). For the electrode arrangement described above, the geometric factor was $34\pi/49$. The resistivity datasets were then de-spiked by visually identifying and removing isolated outliers, and interpolated to a cell size of 0.125 m by 0.125 m to aid visual interpretation. Each dataset was subsequently de-trended by the fitting and removal of a third order polynomial surface. Each processed dataset was then normalised by dividing its values by the dataset's standard deviation. As a result of trend removal and normalisation, respectively, each dataset had a mean of zero and a standard deviation of one. This made it straight forward to make comparisons between datasets.

2.3 Analysis of the raw survey data

It was important to identify seasonal variation in the raw resistivity data in order to help understand whether this affected the resistivity responses of the graves. The average and the standard deviation of the raw datasets after de-spiking were calculated and results analysed for seasonal patterns. The standard deviation values were used as a measure of the noise levels in the respective survey datasets.

2.4 Identification and analysis of grave-related anomalies

In studying the grave-related anomalies, sub-areas measuring 2.5 m by 1.75 m around each of the three graves were identified (Fig. 2a). These areas included borders of approximately 0.5 m around the edges of the graves because low resistivity anomalies that appeared to be grave-related extended beyond the graves' surface outlines. These anomalies were most probably caused by the seeping of grave fluid into the soil around the graves. Any values within these areas that were above +2 SD or below -2 SD were respectively classed as high or low resistivity grave-related anomalies. The thresholds of ±2 SD were chosen to be low enough to include features thought to be caused by the graves, but high enough to exclude most of the noise in the data.

To study variation in the graves resistivity responses, it was necessary to obtain a value that summarised how well each grave was detected. To do this, the ‘volume’ bounded by the surface of each grave's anomaly and the threshold was calculated (Fig. 2b). This quantity was equal to the area bounded by the relevant threshold multiplied by the average residual value of the anomaly, which we define as the difference between the anomaly's average value and the threshold. Technically, this was not a volume, since it was the product of a normalised value (measured in standard deviations) and an area. As such, we shall refer to this quantity, which had units of $m^2 \cdot SD$, as an anomaly’s ‘residual volume. The residual volume reflected both the size of an anomaly and by how much it exceeded the relevant threshold. Both of these properties were considered useful indicators of how well the grave was detected, since a large anomaly that greatly exceeded the threshold value would be easy to identify.

2.5 Calculation of the soil moisture budget

The soil moisture budget was calculated in order to assess whether it influenced the grave-related anomalies' residual volumes. Weather data was obtained from Keele University's weather station, which was located about 200 m from the experimental site. During the study period, monthly rainfall ranged from 21.6 mm to 166.7 mm and the average monthly temperature ranged from -1.2°C to 15.8°C. The weather data and a modified version of Thornthwaite's (1948) method were used to calculate soil moisture budgets for periods of 30 to 210 days. First, monthly evapotranspiration values were calculated following Thornthwaite's method. These values were then divided by the number of days in the month and multiplied by 30 to give 30-day evapotranspiration estimates. These values were taken to represent the evapotranspiration during the 30 days to the end of each month. The estimated evapotranspiration followed a reasonably smooth annual pattern (with peaks around July and lows around February), and these values were interpolated to give a 30-day evapotranspiration value for every day of the project. Each evapotranspiration value was subtracted from the total rainfall in the same 30-day period to give 30-day soil moisture budget estimates. Moisture budgets for periods of 60, 90, 120, 150, 180 and 210 days were calculated by summing moisture budgets for consecutive 30 day periods. Soil moisture budgets for the periods up to the end of the day before each survey were then used for comparison with the anomalies' residual volumes (Fig. 3).

2.6 Regression analysis

Regression analysis (with least squares fitting) was used to estimate linear relationships between the anomalies' residual volumes, the soil moisture budgets, and the properties (i.e. the average and standard deviation) of the raw survey data. In calculating these relationships, the reciprocals of the raw datasets’ properties were used, because resistivity values and their standard deviations have both been shown to be inversely proportional to the soil moisture budget (e.g. Al Chalabi and Rees, 1962; Binley et al., 2002).

3. Results

3.1 The raw resistivity data

The general pattern in the standard deviation of the raw resistivity datasets was one of relatively low values in the early part of each year followed by much higher values later on (Fig. 4). The standard deviation was reasonably constant at around 11 Ω·m between January and April, after which it increased until September and then decreased back towards 11 Ω·m. The average resistivity did not follow quite such an obvious pattern as the standard deviation. However, some peaks in the average resistivity occurred at approximately the same time as those in the standard deviation data.

The inverse of the raw datasets' standard deviation was moderately correlated (R^2>0.5) with the soil moisture budgets calculated for periods of 90 to 210 days (Fig. 5). The closest correlation was 0.77, and this was for the relationship with the 150-day soil moisture budget. The inverse of the average resistivity was not well correlated (R^2<0.3) with any of the soil moisture budgets calculated for this study.

3.2 The empty grave

The empty grave was associated with a high resistivity anomaly (Fig. 6). This anomaly was absent for most of 2008, and its residual volume was less than 0.1 $m^2 \cdot SD$ even when it was present. In 2009, the anomaly was present more often and its residual volume was slightly higher. There was a peak in the anomaly’s residual volume between April and October, and its maximum value was 0.19 $m^2 \cdot SD$. The anomaly’s residual volume was higher still in 2010, with a maximum value of 0.82 $m^2 \cdot SD$. There was a peak in the anomaly’s residual volume between April and the end of the year. The residual volume of the empty grave’s anomaly was not well correlated (R^2<0.3) with any of the soil moisture budgets. Similarly, the anomaly’s residual volume was not well correlated with the inverse values of the average or the standard deviation of the raw datasets.

3.3 The pig grave

The residual volume of the pig grave's low resistivity anomaly varied noticeably during the study period (Fig. 7). The anomaly's residual volume increased from the start of the study until April 2008, when it reached its maximum value of 2.7 $m^2 \cdot SD$, before decreasing down to ~0.5 $m^2 \cdot SD$. Further peaks in its residual volume followed in late-2008/early-2009 and late-2009/early-2010. The anomaly's residual volume was much smaller between these peaks and its lowest value, which occurred in August 2009, was ~0.04 $m^2 \cdot SD$.

The peaks in the anomaly's residual volume all occurred at around the same time of year, which was approximately between November and May. These peaks became smaller and shorter-lived in each successive year. The relative lows in the anomaly's residual volume all lasted roughly from June to October and each low lasted longer than its predecessor.

The anomaly’s residual volume was moderately correlated with the 150-day and 180-day soil moisture budgets (R^2=0.57 and R^2=0.59 respectively; Fig. 8). The residual volume was also moderately correlated with the inverse of the raw datasets' standard deviation (R^2=0.53).

No high resistivity anomalies were identified for the pig grave at the +2 SD threshold.

3.4 The wrapped pig grave

The residual volumes of both the high and low resistivity anomalies associated with the wrapped pig grave varied throughout the study period (Fig. 9). The high resistivity anomaly's residual volume was usually larger than that of the low resistivity anomaly, but both anomalies' residual volumes were zero on several occasions. The peaks in the high and low resistivity anomalies' residual volumes appeared to alternate: the low resistivity peaks occurred midway between the main high resistivity peaks, and vice versa.

The high resistivity anomaly's residual volume was relatively large, at 0.5 m^2·SD, shortly after burial. Its residual volume subsequently decreased until it reached zero in May 2008. In 2009, the anomaly's residual volume recovered somewhat and there was a small peak of 0.15 m^2·SD in April. In 2010, the anomaly's residual volume was larger and its peak value in that year also occurred in April (0.54 m^2·SD).

The low resistivity anomaly was not present for much of the study. There were brief peaks in this anomaly's residual volume in around October in all three years of the study, but these peaks did not exceed 0.02 m^2·SD.

The residual volumes of the grave’s high and low resistivity anomalies were not well correlated (R^2<0.3) with either the inverse of the averages or the standard deviations of the raw datasets, or indeed any of the soil moisture budgets.

4. Discussion

The results of this study showed evidence of seasonal electrical resistivity variations as annually repeating patterns in the properties of the raw datasets and the resistivity responses of the graves.

From reviewing the datasets collected, it may seem surprising that the standard deviation of the raw datasets was more closely related than the average resistivity to the soil moisture budget. However, the wide separation between the mobile and the reference electrodes means that relatively deep soil between the electrode pairs influences resistivity measurements made with the twin probe array. The resistivity of this deeper soil would be much more stable than that of the near-surface soils, which may explain why the average resistivity measured in this study does not exhibit much seasonal variation. The variation in resistivity measurements made with the twin probe array comes from the movement of the mobile electrodes between each measurement. The closely-spaced mobile electrodes are more sensitive to near surface changes in resistivity, and the resistivity of this near surface soil is more likely to vary seasonally (see Reynolds, 2011). This may explain why the standard deviation of the raw resistivity datasets exhibited a seasonal pattern and was well correlated with the soil moisture budget. So even if there is no variation in the resistivity response of a target feature, there may be certain times of the year that are best for resistivity surveys because of variation in the noise levels. In this study, the noise levels were lowest in collected datasets between approximately January and April of each year.

The exact reason for the correlation between the standard deviation and the soil moisture budget is not clear. One possibility is that the resistivity of the near surface soil was relatively homogeneous when the soil was wet, but natural heterogeneities became more pronounced as the soil dried out.

Although disturbed soil is usually expected to cause low resistivity anomalies, the empty grave in this study was associated with a high resistivity anomaly. This anomaly was not particularly noticeable during the first two years of the study, but it was more obvious in the third year. The year on year increase in this anomaly's residual volume could have been caused by the gradual drying out of the grave soil in dry weather. This explanation is consistent with the fact that the annual peaks in the anomaly's residual volume occurred in the summer months when the 30-day soil moisture budget was typically negative. It seems likely that disturbing the soil to create the grave affected the soil's ability to retain moisture.

There may have been some seasonal variation in the empty grave's residual volume, even though it was not well correlated with the soil moisture budget. The rise and fall in the anomaly's residual volume in 2010 could have been the beginning of an annual pattern. The 2010 peak in the anomaly's residual volume occurred when the 30-, 60- and 90-day soil moisture budgets were negative. The grave's resistivity could, therefore, have been a result of seasonal wetting and drying of the grave soil that was a result of changes in the short-term soil moisture budget.

The pattern in the residual volume of the pig grave's anomaly was suggestive of seasonal variation because it was broadly similar in each year of the study. This variation was large enough to determine whether the grave could be detected: when its residual volume was low, the anomaly was difficult to identify in the resistivity data (Fig. 1 cf. Fig. 7). The anomaly's residual volume was inversely proportional to the raw datasets' standard deviation, which suggests the noise levels in the survey data affected the anomaly's appearance. The anomaly itself may have been relatively constant while being alternately obscured when the data was noisy and revealed when the data was less noisy. In terms of the signal-to-noise ratio, therefore, it is suggested that it was the noise and not the signal that varied seasonally. If the soil moisture budget did cause the variation in the resistivity data's noise levels, it would also have been the ultimate cause of the seasonal variation in the pig grave anomaly's residual volume.

Some features in the residual volume of the pig grave anomaly did not appear to be part of a seasonal pattern. The prolonged initial increase in the anomaly's residual volume, for example, was not repeated in the later years of the project. This increase could be attributed to the accumulation of grave fluid in the soil during the most active phase of the cadaver's decomposition (see Pringle et al. 2012a). Another pattern that did not appear to be seasonal was the decrease in the maximum residual volume of the anomaly in each successive year of the project. This could have been caused by a gradual drainage of grave fluid to a depth at which it could no longer be detected. Another possibility is that the grave soil gradually dried out (as we suggest happened in the empty grave), and the corresponding rise in soil resistivity counteracted the low resistivity effect of the grave fluid. So, as well as seasonal factors, internal processes occurring within the grave may well have influenced its anomaly's residual volume. However, the correlation of 0.59 suggests that the soil moisture budget can explain more than half the variation in the pig grave anomaly's residual volume. The majority of the variation in this anomaly's residual volume during the project may, therefore, have been seasonal.

The evidence for seasonal patterns in the residual volume of the wrapped pig grave's anomalies was less clear. The high resistivity anomaly was the grave's main anomaly because it was detected more often and was typically larger in residual volume than the low resistivity anomaly. The patterns in the high resistivity anomaly's residual volume were primarily decline in 2008 and recovery in 2010. These patterns can be explained by the same processes of accumulation and, subsequently, drainage of grave fluid that is suggested to have happened within the pig grave. The accumulation of grave fluid, which could have counteracted the high resistivity effect of the tarpaulin-wrapped cadaver, could have caused the rapid decline in the anomaly's residual volume shortly after burial. Equally, the recovery in residual volume in 2010 could have been a result of the grave fluid’s draining away. Alternatively, as with the empty grave, the increase in the high resistivity anomaly’s residual volume towards the end of the study could have been caused by the grave soil’s drying out. The variation in the anomaly's residual volume in 2010 may also have been partly seasonal. The pattern of increasing residual volume up to a peak in April followed by decline throughout the rest of the year was similar to (although not the same as) the seasonal pattern in the pig grave anomaly's residual volume. Furthermore, although the high resistivity anomaly's residual volume was much smaller in 2009 than in 2010, the general patterns in both years were similar. Perhaps the grave fluid in the wrapped pig grave began to drain in 2009, which lead to a decrease in the interaction between the high and low resistivity anomalies. Seasonal variation in the resistivity data's noise levels could then have started to affect the high resistivity anomaly's residual volume. By the time more fluid had drained away in 2010, seasonal variation in the anomaly's residual volume could have become more pronounced.

The residual volume of the low resistivity anomaly associated with the wrapped pig grave also seemed to follow a seasonal pattern because it peaked at about the same time each year. Unlike the pig grave's low resistivity anomaly, the wrapped pig grave anomaly's residual volume peaked around the time of highs in the raw datasets' standard deviation. It therefore seems unlikely that the residual volume of the wrapped pig grave's low resistivity anomaly was related to the resistivity data's noise levels: it was unlikely that the anomaly would be easiest to detect when the data was noisiest. The anomaly's residual volume may instead have been directly related to the soil moisture budget. The peaks in the low resistivity anomaly's residual volume occurred during lows in the 180-day soil moisture budget. When the soil was particularly dry, hydraulic gradients may have drawn the grave fluid through the weave of the tarpaulin and into the surrounding soil where it could more easily be detected.

In terms of variation in the anomalies, it was perhaps the pig grave anomaly and the wrapped pig grave's high resistivity anomaly that had most in common. Both anomalies may, to a greater or lesser degree, have been affected by the accumulation and drainage of grave fluid and by seasonal factors. It is suggested that the seasonal variation in these anomalies was caused by variation in the resistivity datasets' noise levels, which was in turn caused by the seasonal soil moisture budget. This is quite different to the causes of seasonal variation that have been suggested by others (e.g. see Clark, 1996). Furthermore, the fact that some resistivity anomalies are easiest to detect when the soil moisture budget is negative suggests that the seasonal variation they exhibit is different to that observed here. This is perhaps not too surprising, since the results for both wrapped pig grave anomalies suggest that internal changes within a detectable subsurface feature can override seasonal variation related to fluctuating noise levels in resistivity data. Thus, it seems there may be two types of seasonal variation: that related to direct interaction between a subsurface feature and the soil moisture budget, and that related to variation in the noise levels of resistivity data (which may itself be governed by the soil moisture budget).

5. Conclusions

This study results show that seasonal weather patterns can affect the ability of resistivity surveys to detect clandestine graves. Based on the results for the pig grave, it seems that the best conditions for locating recent burials occur around the time of the annual maximum in the 180-day soil moisture budget, which in this study was between January and April each year.

It is suggested that the changing soil moisture budget caused seasonal variation in the resistivity data's noise levels, which in turn caused variation in the pig grave's resistivity anomaly. However, for much of the study, the wrapped pig grave's high and low resistivity anomalies seemed to be relatively unaffected by this variation. It seems that internal changes (related to the fluid that was partially trapped in the tarpaulin) within the grave were the primary cause of variation in its resistivity anomalies. These internal changes may, therefore, have obscured any effect that seasonal variation in the resistivity data's noise levels may have had on the grave's anomalies. Towards the end of the study there was some evidence of noise-related seasonal variation in the high resistivity anomaly's residual volume.

Seasonal variation in the grave-related anomalies that was caused by variation in the resistivity data's noise levels would be unrelated to processes occurring within the graves. This type of variation could affect the detection of other types of subsurface feature, as long as there was no major internal variation within the feature that affected its resistivity.

There could, therefore, be times of the year that provide the best conditions for resistivity surveys because the noise levels in the resulting data will be low. Since the standard deviation of our datasets was moderately correlated with the soil moisture budget, it would be possible to use existing weather data to predict when the best conditions occur. However, seasonal variation in the noise levels in resistivity data may be different for climates and soil types that are different to those present at our study location. As such, we recommend further research be conducted to study the effect of local climate on the detection of graves and other features in a range of environments.

Acknowledgements

Jamie Hansen (a PhD student at Keele University) is thanked for assistance with data collection. Two open source software packages were particularly useful for this project: Generic Mapping Tools (GMT) software was used to analyse the resistivity data and prepare figures, and R software to perform regression analysis. This study was partially based on the lead author’s PhD research, which was funded by the EPSRC and RSK Stats Ltd. The comments of two anonymous reviewers helped to improve this paper.

References

Aaltonen, J., Olofsson, B., 2002. Direct current (DC) resistivity measurements in long-term groundwater monitoring programs. Environ. Geol. 41, 662-671. DOI:10.1007/s00254-001-0447-1

Al Chalabi, M.M., Rees, A.I., 1962. An experiment on the effect of rainfall on electrical resistivity anomalies in the near surface. Bonn. Jahrb. 162, 266-271.

Binley, A., Winship, P., West, L.J., Pokar, M., Middleton, R., 2002. Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar and resistivity profiles. J. Hydrol. 267, 160-172. DOI:10.1016/S0022-1694(02)00147-6

Buck, S.C., 2003. Searching for graves using geophysical technology: field tests with ground penetrating radar, magnetometry and electrical resistivity. J. Forensic Sci. 48, 1-7. DOI:10.1520/JFS2002165

Cheetham, P., 2005. Forensic geophysical survey, in: Hunter, J., Cox, M. (Eds.), Forensic Archaeology: Advances in Theory and Practice. Routledge, Oxon, pp. 62-95. ISBN:0415273129

Clark, A.J., 1996. Seeing Beneath the Soil: Prospecting Methods in Archaeology, first rev. ed. Batsford Ltd., London. ISBN:0415214408

Ellwood, B.B., 1990. Electrical resistivity surveys in two historical cemeteries in northeast Texas: a method for delineating unidentified burial shafts. Hist. Archaeol. 24, 91-98. ISSN:0440-9213

Ellwood, B.B., Owsley, D.W., Ellwood, S.H., Mercado-Allinger, P.A., 1994. Search for the grave of the hanged Texas gunfighter, William Preston Longley. Hist. Archaeol. 28, 94-112. ISSN:0440-9213

Friedman, S.P., 2005. Soil properties influencing apparent electrical conductivity: a review. Comput. Electron. Agric. 46, 45-70. DOI:10.1016/j.compag.2004.11.001

Hammon, W.S., McMechan, G.A., Zeng, X., 2000. Forensic GPR: finite-difference simulations of responses from buried human remains. J. Appl. Geophys. 45, 171-186. DOI:10.1016/S0926-9851(00)00027-6

Jervis, J.R., 2010. The detection of clandestine graves using electrical resistivity surveys: results from controlled experiments and a case study. Unpublished PhD thesis, Keele University.

Jervis, J.R., Pringle, J.K., Cassella, J.P., Tuckwell, G., 2009a. Using soil and groundwater data to understand resistivity surveys over a simulated clandestine grave, in: Ritz, K., Dawson, L., Miller, D. (Eds.), Criminal and Environmental Soil Forensics. Springer

Science+Business Media B.V., Dordrecht, pp. 271-284. ISBN:978-1-4020-9203-9

Jervis, J.R., Pringle, J.K., Tuckwell, G.W., 2009b. Time-lapse resistivity surveys over simulated clandestine graves. Forensic Sci. Int. 192, 7-13. DOI:10.1016/j.forsciint.2009.07.001

Juerges, A., Pringle, J.K., Jervis, J.R., Masters, P., 2010. Comparisons of magnetic and electrical resistivity surveys over simulated clandestine graves in contrasting burial environments. Near Surf. Geophys. 8, 529-539. DOI:10.3997/1873-0604.2010042

Powell, K., 2010. Grave Concerns: Locating and Unearthing Human Bodies. Australian Academic Press, Bowen Hills. ISBN:1921513705

Pringle, J.K., Jervis, J.R., 2010. Electrical resistivity survey to search for a recent clandestine burial of a homicide victim, UK. Forensic Sci. Int. 202, e1-e7. DOI:10.1016/j.forsciint.2010.04.023

Pringle, J.K., Ruffell, A., Jervis, J.R., Donnelly, L., McKinley, J., Hansen, J., Morgan, R., Pirrie, D., Harrison, M., 2012a. The use of geoscience methods for terrestrial forensic searches. Earth-Sci. Rev. 114, 108-123. DOI:10.1016/j.earscirev.2012.05.006

Pringle, J.K., Holland, C., Skornik, K., Harrison, M., 2012b. Establishing forensic search methodologies and geophysical surveying for the detection of clandestine graves in coastal beach environments. Forensic Sci. Int. 219, e29-e36. DOI:10.1016/j.forsciint.2012.01.010

Pringle, J.K., Jervis, J.R., Hansen, J.D., Jones, G.M., Cassidy, N.J., Cassella, J.P., 2012c. Geophysical monitoring of simulated clandestine graves using electrical and ground-penetrating radar methods: 0-3 years after burial. J. Forensic Sci. 57, 1467-1486. DOI:10.1111/j.1556-4029.2012.02151.x

Pringle, J.K., Jervis, J.R., Cassella, J.P., Cassidy, N.J., 2008. Time-lapse geophysical investigations over a simulated urban clandestine grave. J. Forensic Sci. 53, 1405-1416. DOI:10.1111/j.1556-4029.2008.00884.x

Reynolds, J.M., 2011. An Introduction to Applied and Environmental Geophysics, 2nd review edition. John Wiley and Sons. Chichester. ISBN: 0471485365

Ruffell, A., McKinley, J., 2005. Forensic geoscience: applications of geology, geomorphology and geophysics to criminal investigations. Earth-Sci. Rev. 69, 235-247. DOI:10.1016/j.earscirev.2004.08.002

Schultz, J.J., Martin, M.M.., 2012. Monitoring controlled graves representing common burial scenarios with ground penetrating radar. J. Appl. Geophys. 83, 74-89. DOI:10.1016/j.jappgeo.2012.05.006

Scollar, I., Tabbagh, A., Hesse, A., Herzog, I., 1990. Archaeological Prospecting and

Remote Sensing. Cambridge University Press, Cambridge. ISBN: 0521115469

Scott, J., Hunter, J.R., 2004. Environmental influences on resistivity mapping for the location of clandestine graves, in: Pye, K., Croft, D.J. (Eds.), Forensic geoscience: principles, techniques and applications. Geological Society, London, pp. 33-38. ISBN: 1862391610

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geogr. Rev. 38, 55-94. Stable URL: http://www.jstor.org/stable/210739 Last Access: 15/12/2013.

Figure captions

Figure 1: Example processed resistivity survey datasets, showing the resistivity responses of the three graves (a) in late summer (August 2009), and (b) in early spring (March 2010), and demonstrating the seasonal variation in the data. Common scale is standard deviation. The grave corners are indicated by white circles with black centres; the pig grave is on the left side of the figure, the empty grave is in the centre, and the wrapped pig grave is on the right. After Jervis et al. (2009b) and Pringle et al. (2012c).

Figure 2: An illustration of how the grave-related anomalies were identified and their residual volumes were calculated. (a) An example dataset showing the chosen areas for the pig grave, the empty grave, and the wrapped pig grave (dashed black rectangles) and the -2 (solid white lines) and +2 (solid black lines) SD thresholds respectively. (b) A three-dimensional representation of the data that exceeded the +2 threshold within the area chosen for the wrapped pig grave. The residual volume of this anomaly was calculated as that bounded by the surface of this shape and the plane of the +2 SD threshold.

Figure 3: Three of the soil moisture budgets (abbreviated as 'S.M.B.' on the vertical axis) used in this study. The moisture budgets are typically positive in the early part of each year (especially January to June) and negative in the latter part of the year (July to November). This pattern becomes more pronounced as the period over which the moisture budget is calculated increases.

Figure 4: The average (plotted against the left axis) and the standard deviation (plotted

against the right axis) of the raw resistivity survey datasets. After Pringle et al. (2012c).

Figure 5: The relationship between the inverse of the standard deviation of the raw resistivity datasets and the soil moisture budget. (a) Correlation as a function of the soil moisture budget period. (b) Relationship between the inverse of the standard deviation and the 150-day soil moisture budget. The equation for the estimated regression relationship (dashed line) is shown at the top.

Figure 6: The residual volume of the empty grave anomaly. Asterisks indicate values calculated from the two datasets shown in Fig. 1.

Figure 7: The residual volume of the pig grave anomaly. Asterisks indicate values calculated from the two datasets shown in Fig. 1.

Figure 8: Relationships between the pig grave anomaly's residual volume and the soil moisture budget. (a) Correlation as a function of the soil moisture budget period. (b) Relationship between the anomaly's residual volume and the 180-day soil moisture budget. The equation for the estimated regression relationship (dashed line) is shown at the top.

Figure 9: The residual volume of the high resistivity (plotted against the left axis) and low resistivity (plotted against the right axis) wrapped pig grave anomalies. Asterisks indicate values calculated from the two datasets shown in Fig. 1.

Figure1

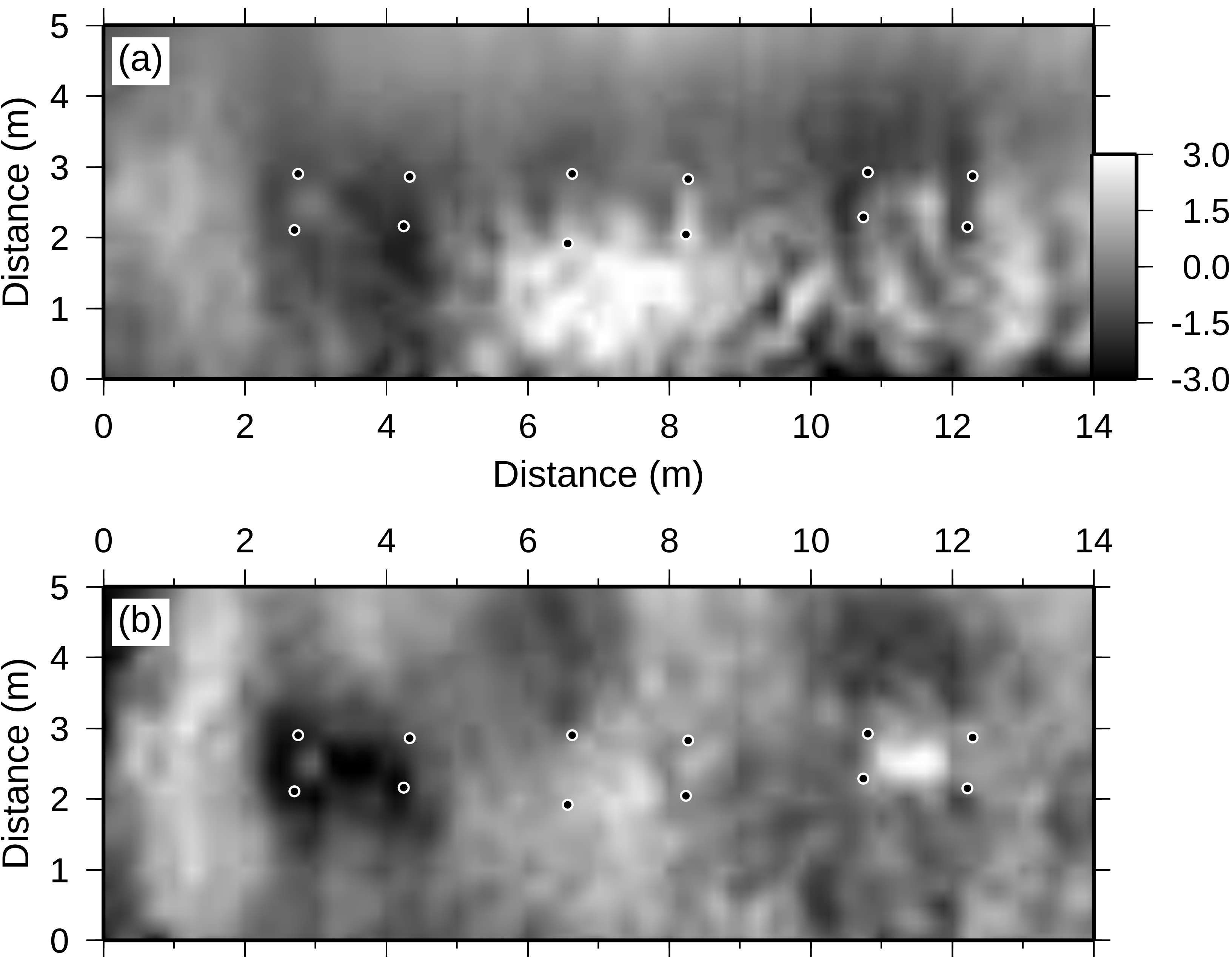
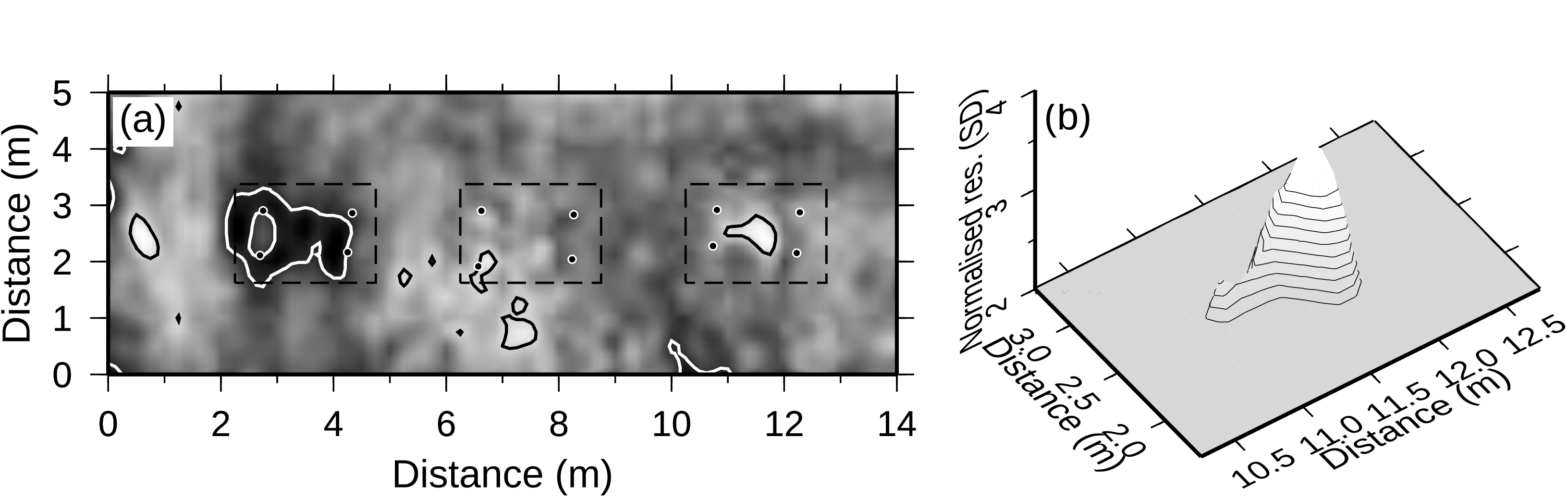
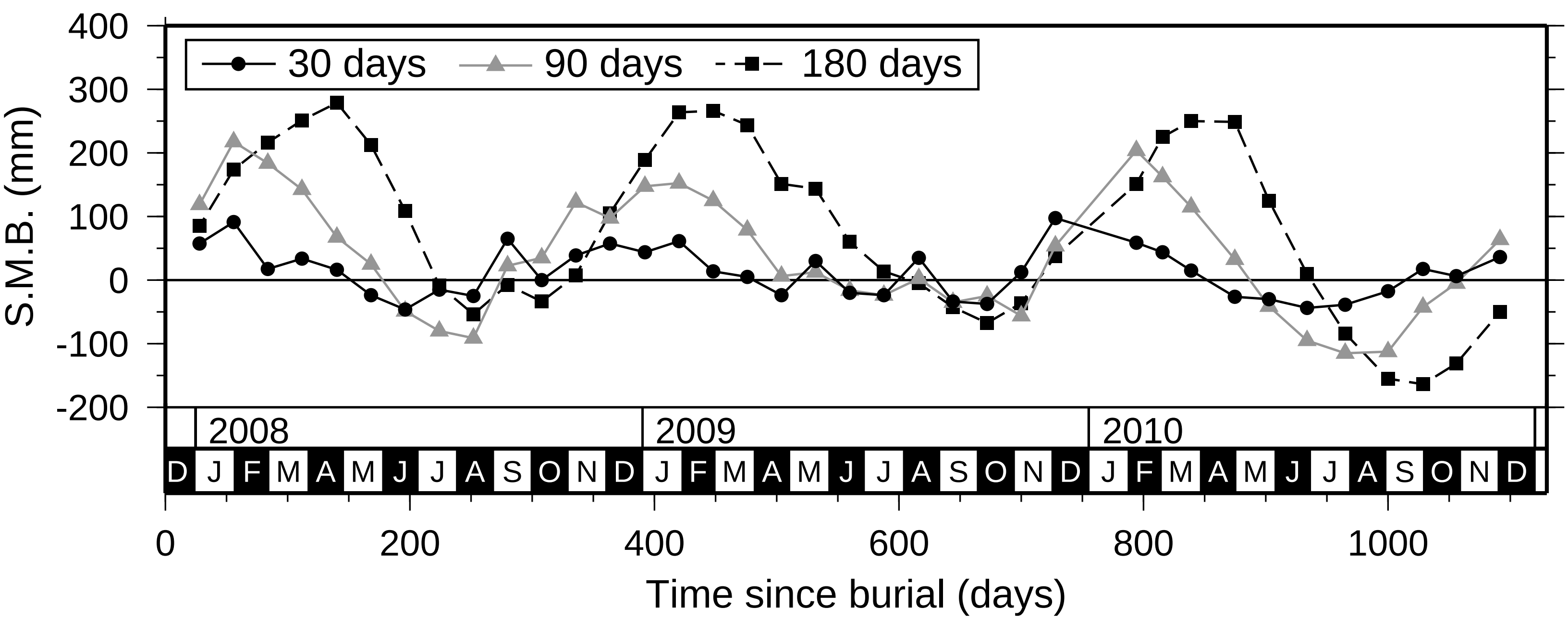

(a)
(b)
Distance (m)
Distance (m)
Distance (m)
0
1
2
3
4
5
0
2
4
6
8
10
12
14
3.0
1.5
0.0
-1.5
-3.0

Figure2



(a)
Distance (m)
Distance (m)
0
1
2
3
4
5
0
2
4
6
8
10
12
14
(b)
Normalised res. (SD)
2
3
4
Distance (m)
3.0
2.5
2.0
Distance (m)
10.5
11.0
11.5
12.0
12.5

Figure3



30 days
90 days
180 days
400
300
200
100
0
-100
-200
S.M.B. (mm)
2008
2009
2010
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
0
200
400
600
800
1000
Time since burial (days)

Figure4

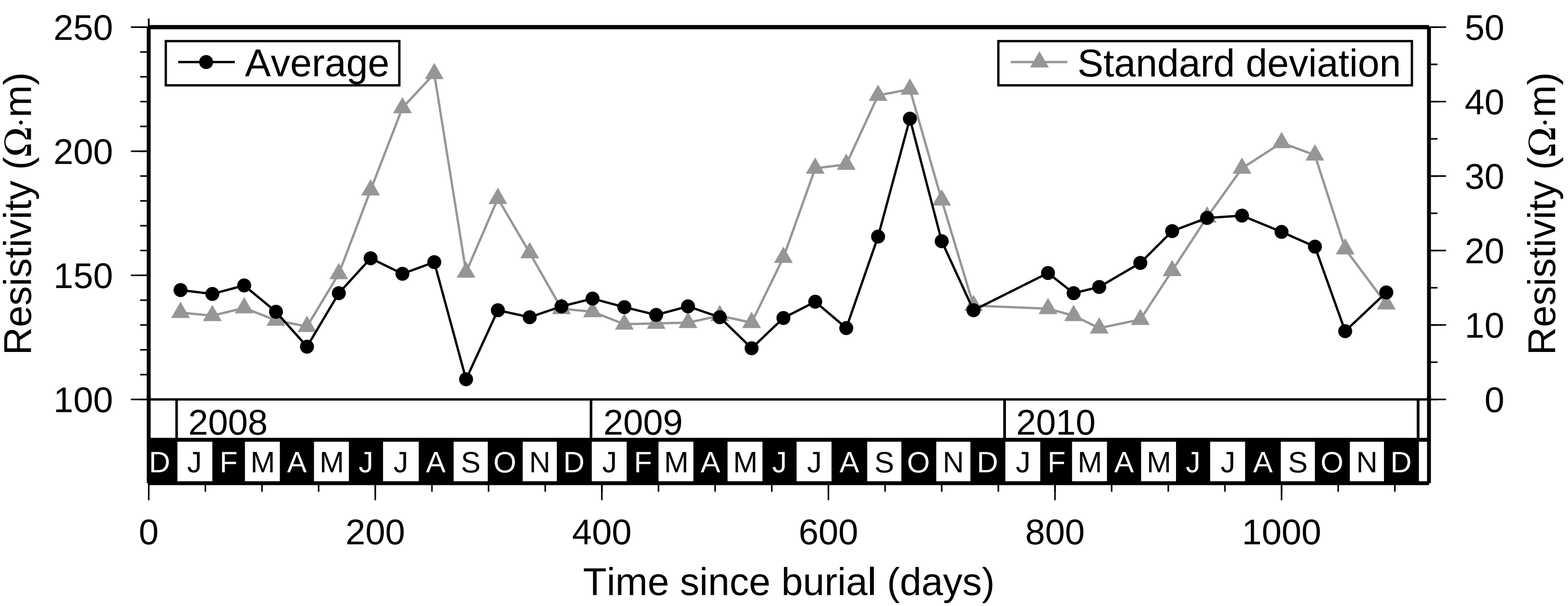
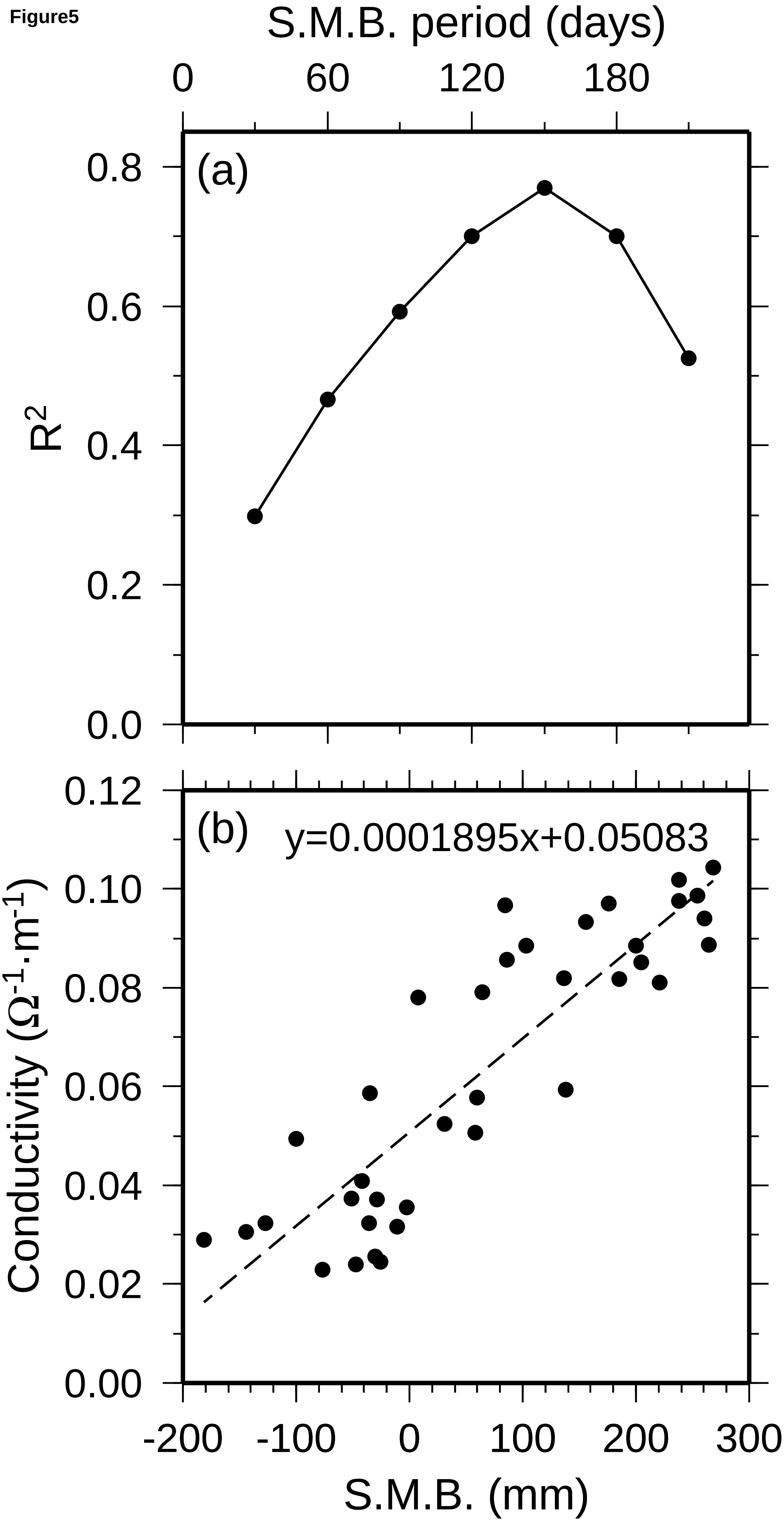
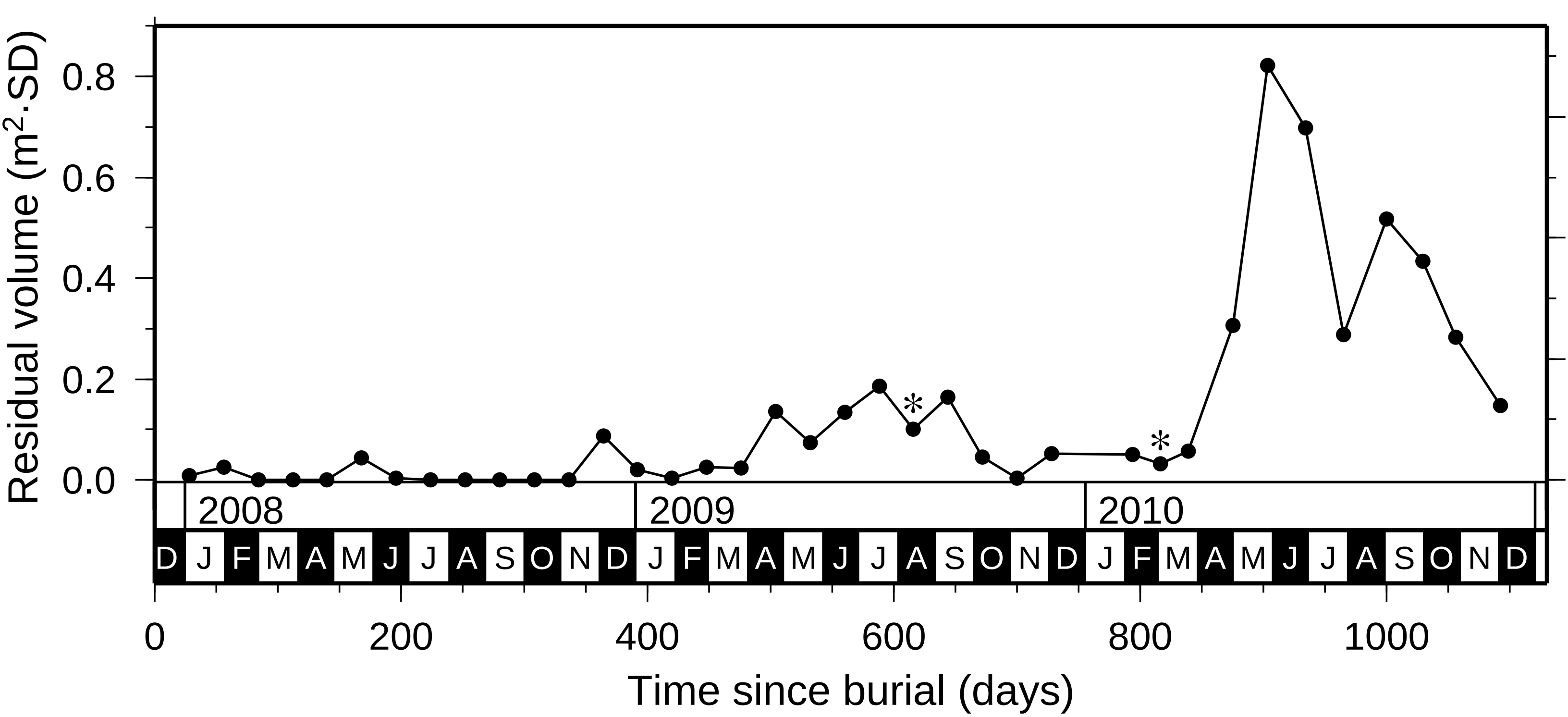

Average
Standard deviation
Resistivity (Ω·m)
Resistivity (Ω·m)
250
200
150
100
50
40
30
20
10
0
2008
2009
2010
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
0
200
400
600
800
1000
Time since burial (days)

Figure5



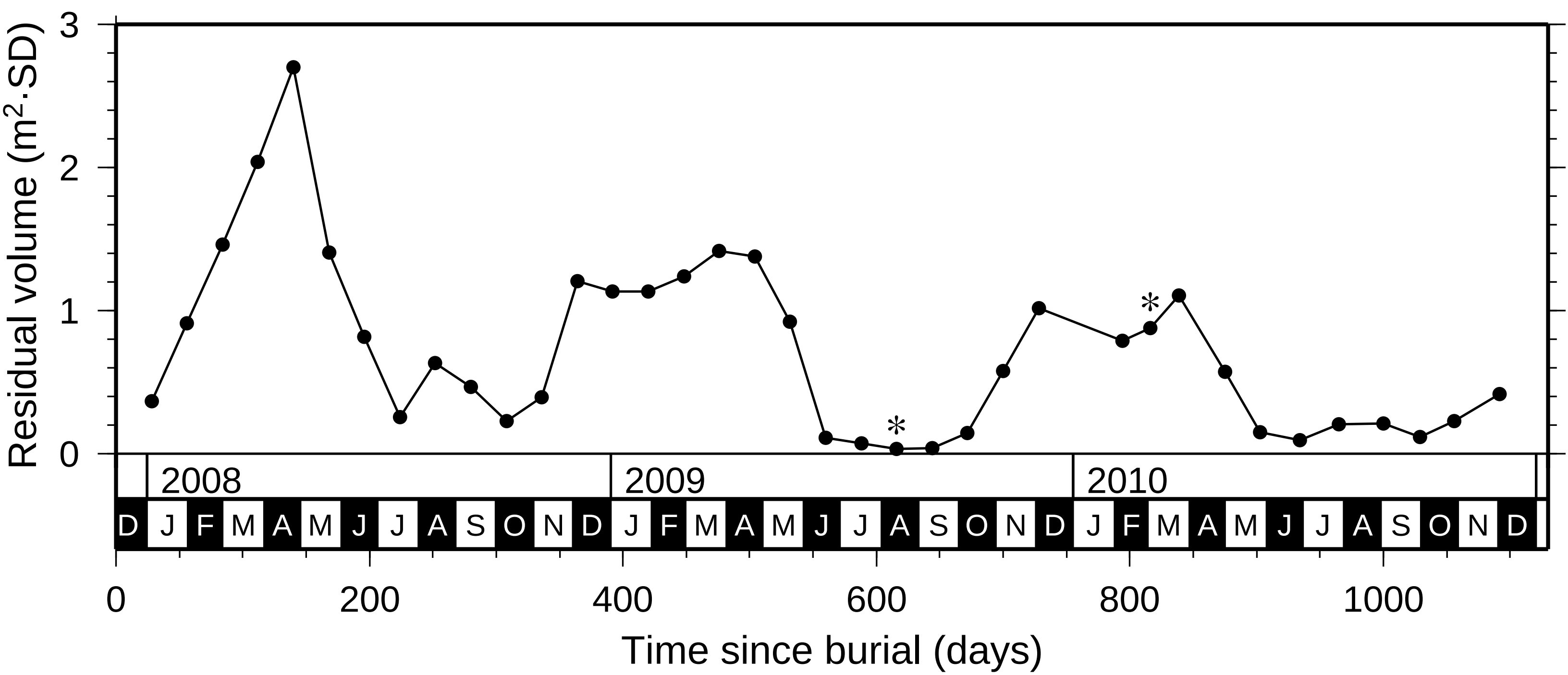
S.M.B. period (days)
0
60
120
180
0.8
0.6
0.4
0.2
0.0
(a)
R^2
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(b)
y=0.0001895x+0.05083
Conductivity ($\Omega^{-1}\cdot m^{-1}$)
-200
-100
0
100
200
300
S.M.B. (mm)

Figure6



Residual volume (m2·SD)
0.8
0.6
0.4
0.2
0.0
2008
2009
2010
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
0
200
400
600
800
1000
Time since burial (days)

Figure7



Residual volume (m²·SD)
3
2
1
0
*
*
2008
2009
2010
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
0
200
400
600
800
1000
Time since burial (days)

Figure8

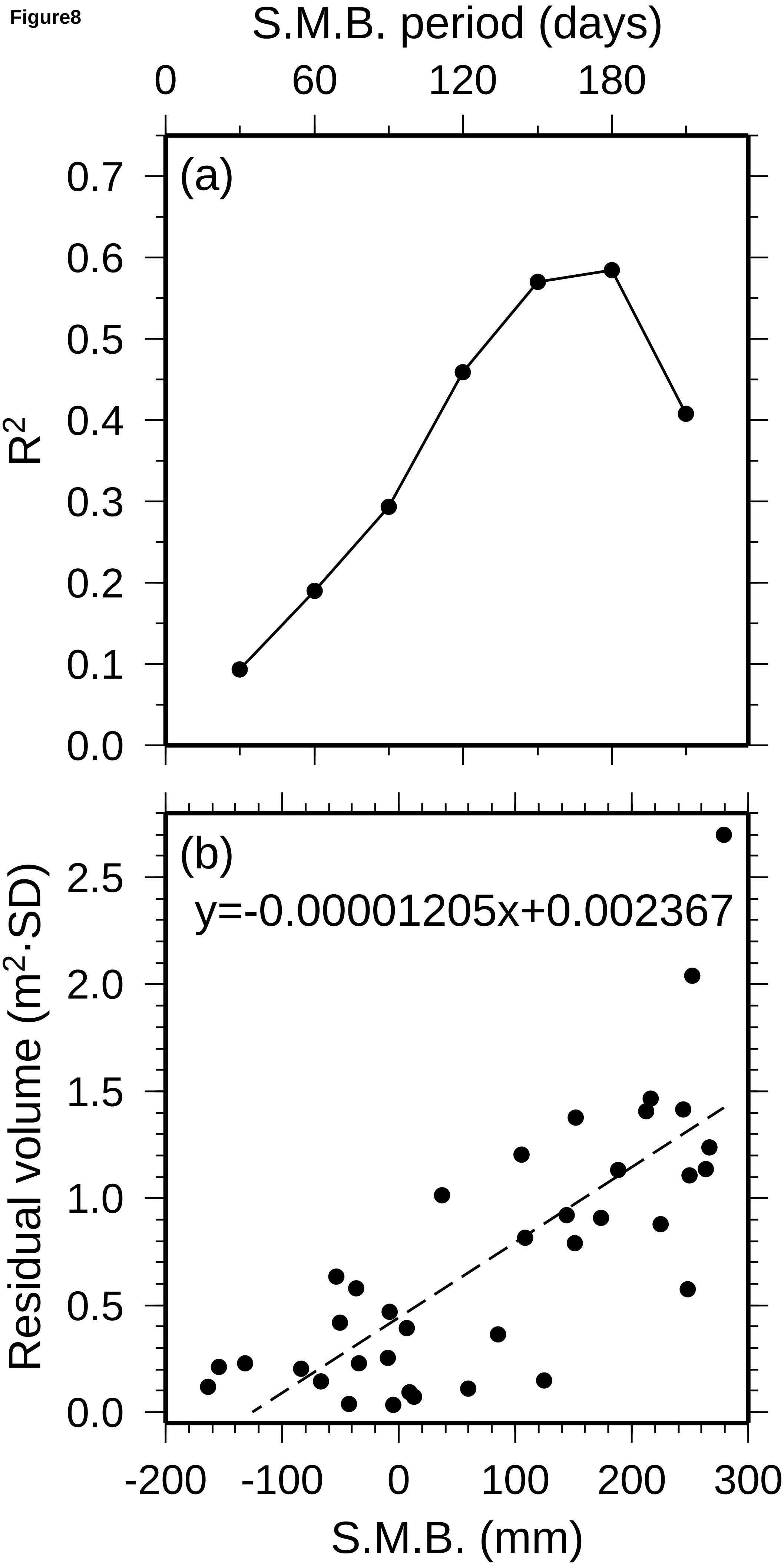
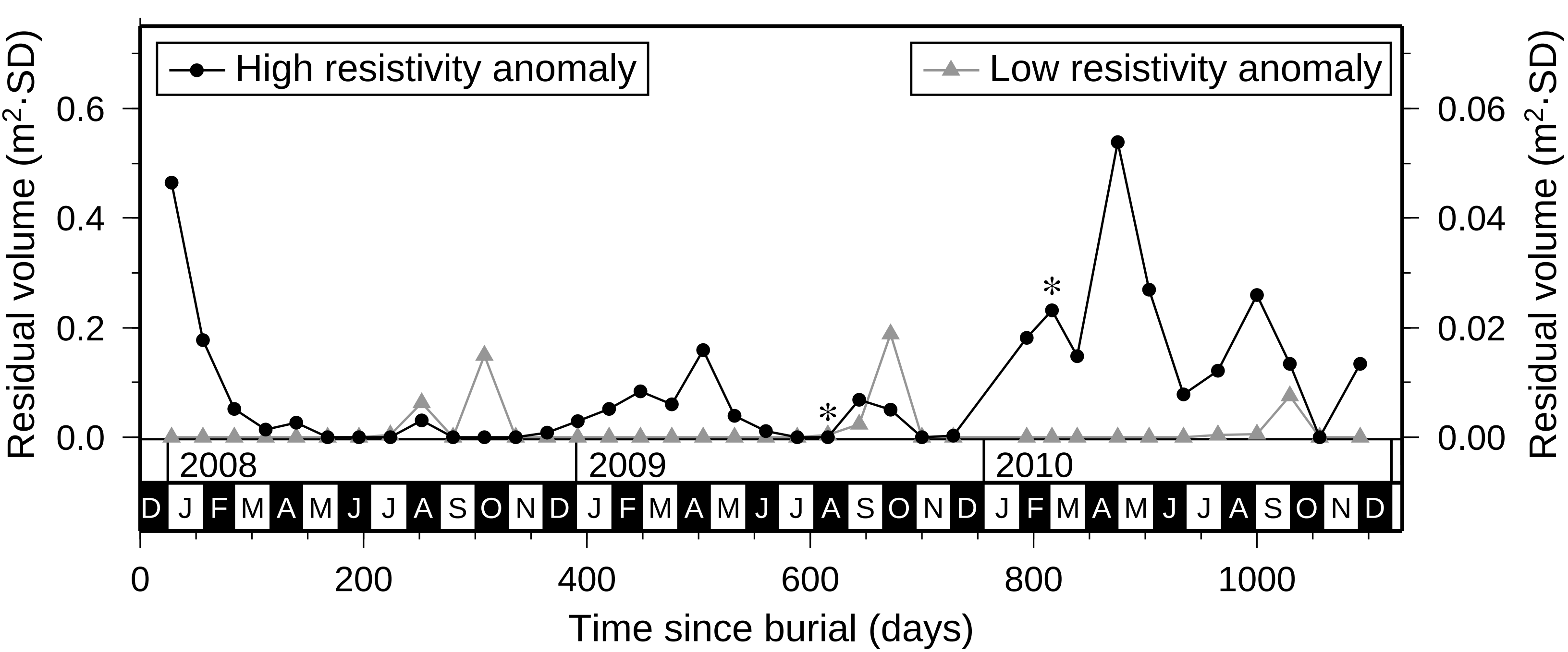

S.M.B. period (days)
0
60
120
180
(a)
R^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
(b)
y=-0.00001205x+0.002367
Residual volume (m^2·SD)
0.0
0.5
1.0
1.5
2.0
2.5
-200
-100
0
100
200
300
S.M.B. (mm)

Figure9



High resistivity anomaly
Low resistivity anomaly
Residual volume (m²·SD)
Residual volume (m²·SD)
0.0
0.2
0.4
0.6
0.00
0.02
0.04
0.06
*
*
2008
2009
2010
D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
0
200
400
600
800
1000
Time since burial (days)

Background dataset

Click here to download Background dataset for online publication only: JR&JP_rawres.xlsx